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Bratkovski et al.

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(54) **MAGNETICALLY ACTIVATED PHOTONIC SWITCHES AND SWITCH FABRICS EMPLOYING THE SAME**

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Related U.S. Application Data

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(51) **Int. Cl.**
G02B 6/26 (2006.01)
G02B 6/42 (2006.01)

(52) **U.S. Cl.** **385/16**; 385/17; 385/50

(58) **Field of Classification Search** 385/16–17
See application file for complete search history.

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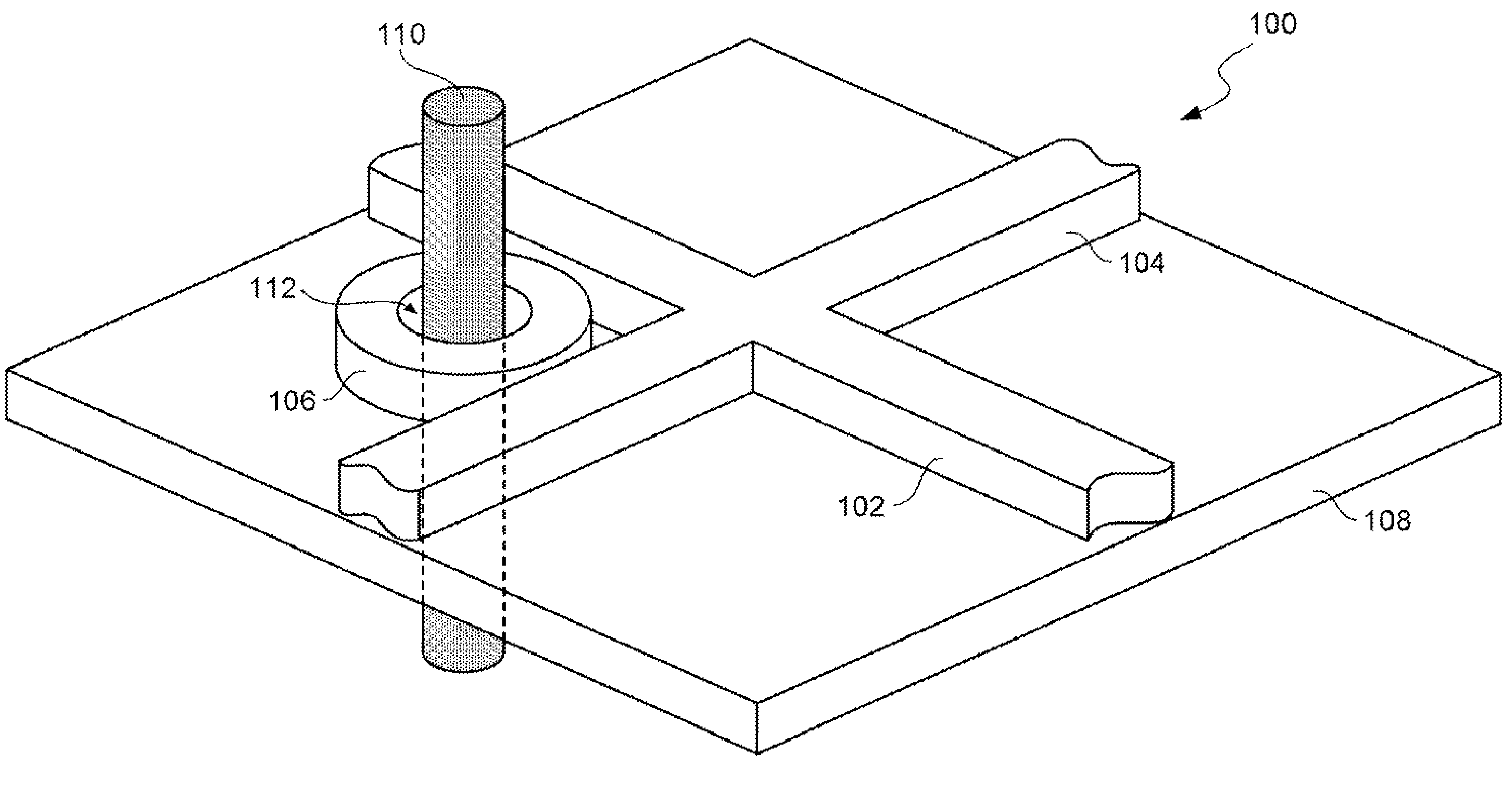
(57) **ABSTRACT**

Various embodiments of the present invention are directed to photonic switches and switch fabrics employing the photonic switches. In one embodiment of the present invention, a photonic switch comprises a first waveguide disposed on a surface of a substrate in proximity to an opening in the substrate, and a second waveguide crossing the first waveguide and positioned in proximity to the opening in the substrate. The photonic switch includes a tunable microring resonator disposed on the surface of the substrate adjacent to the first waveguide and the second waveguide and configured with an opening aligned with the opening in the substrate. The photonic switch also includes a wire having a first end and a second end and configured to pass through the opening in the microring and the opening in the substrate.

20 Claims, 15 Drawing Sheets



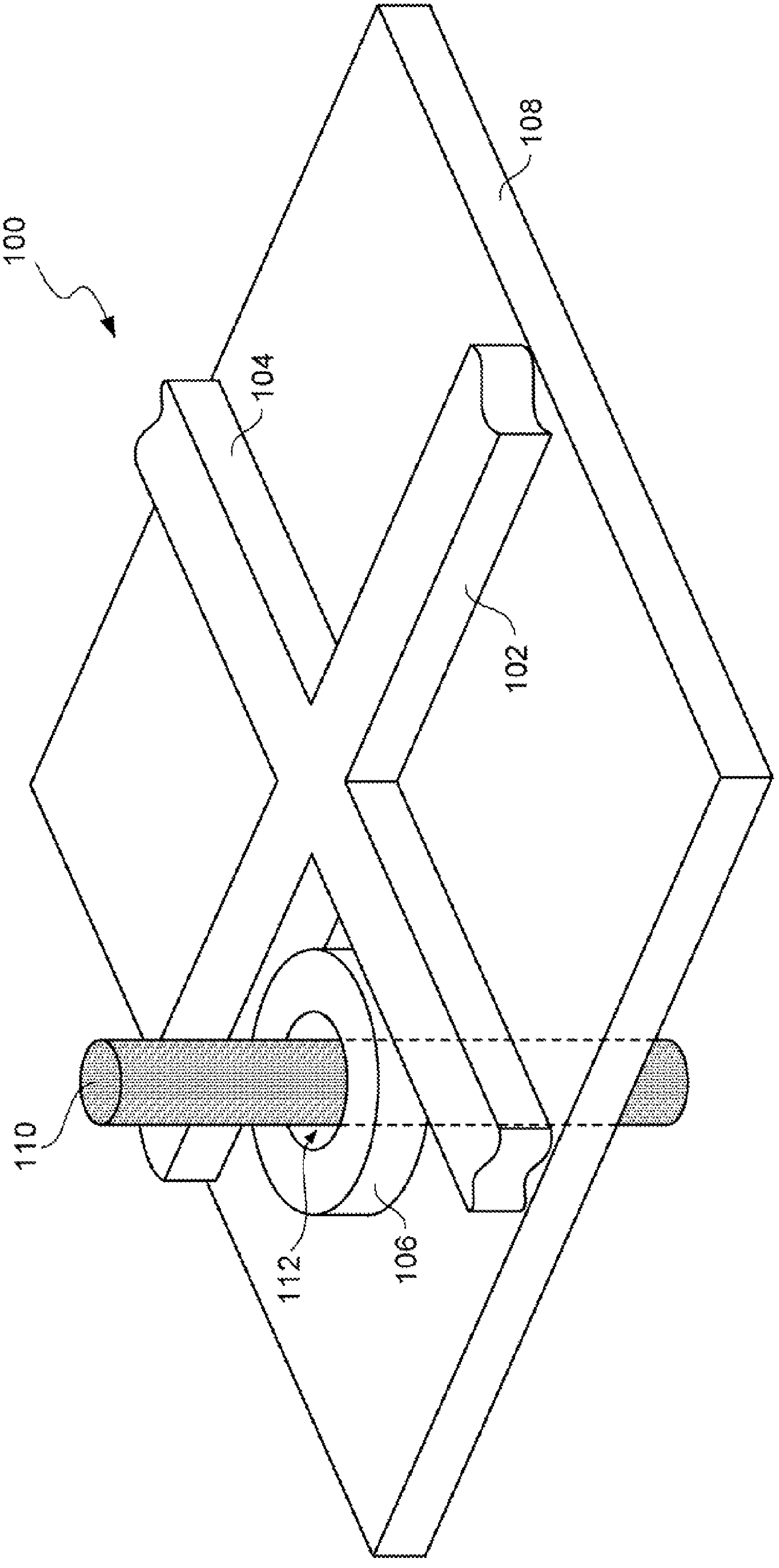
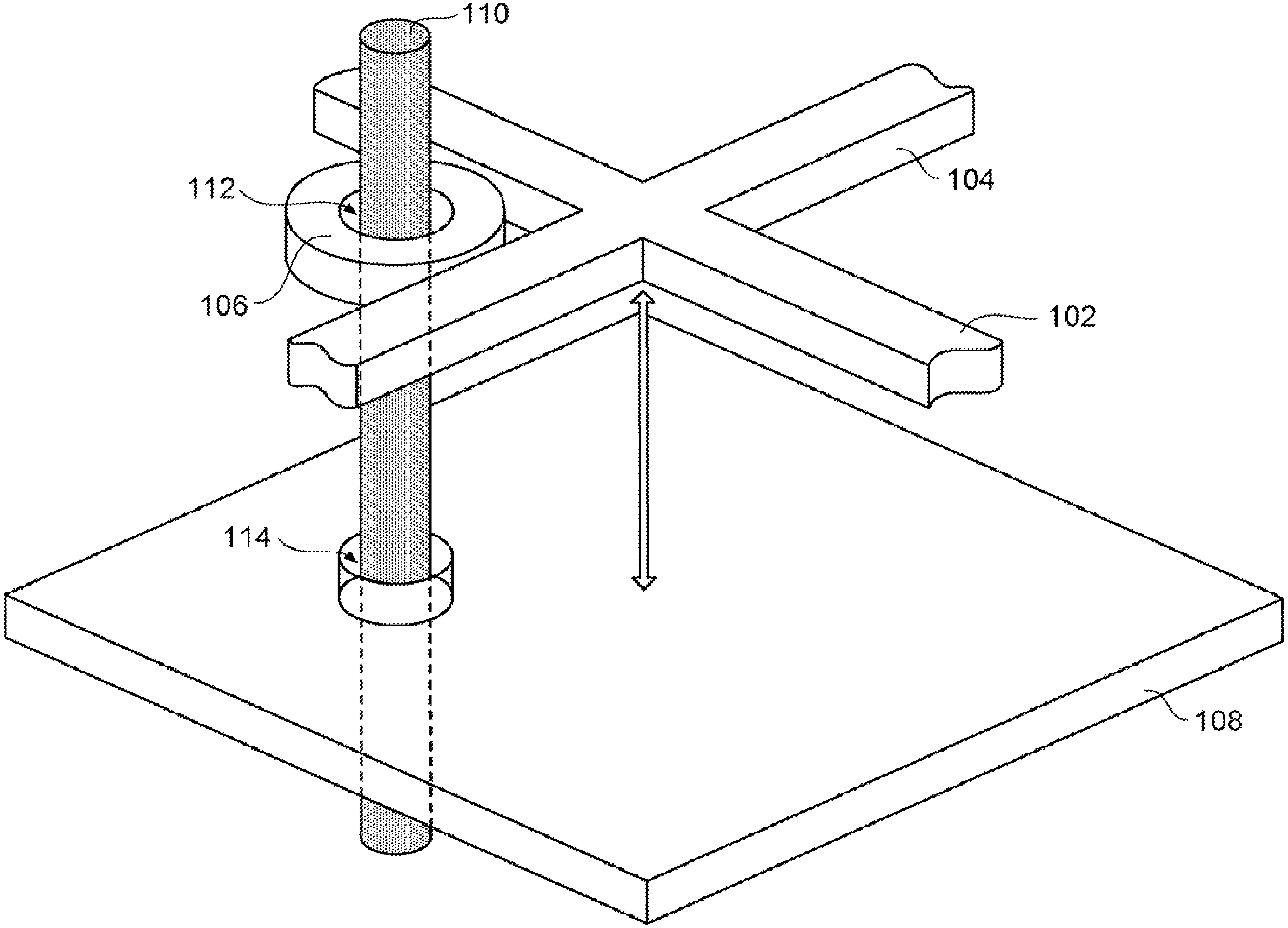


Figure 1A



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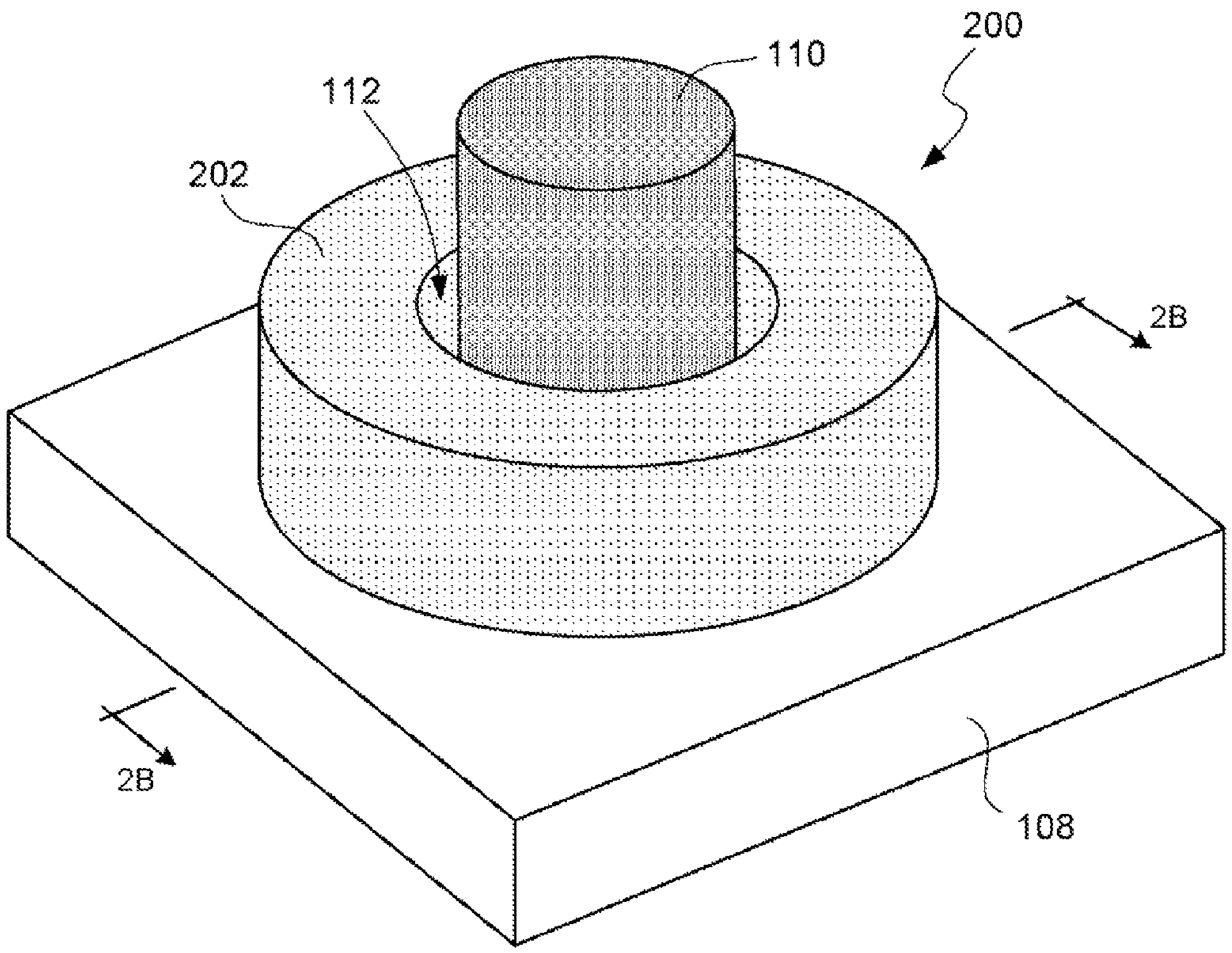


Figure 2A

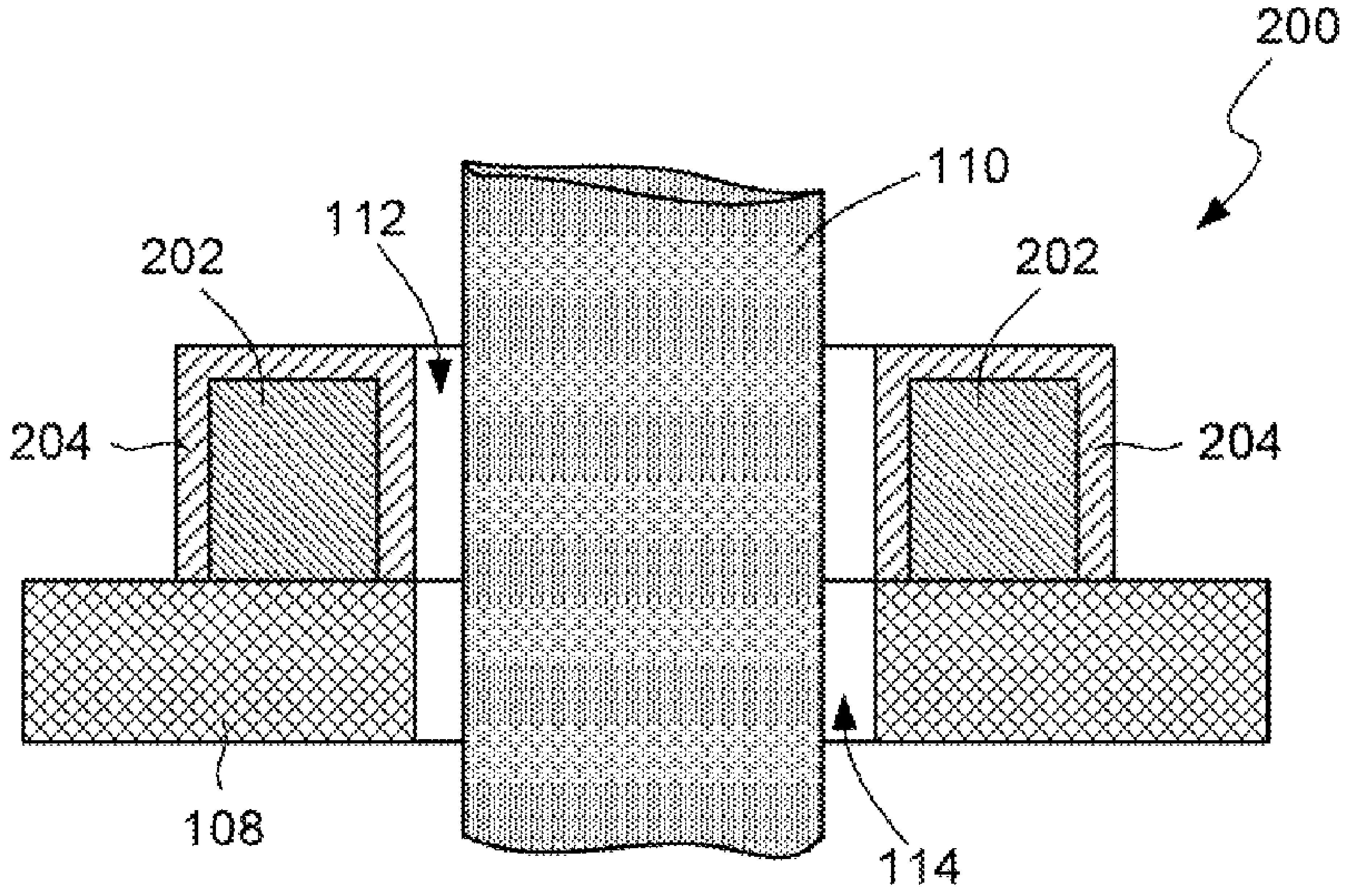


Figure 2B

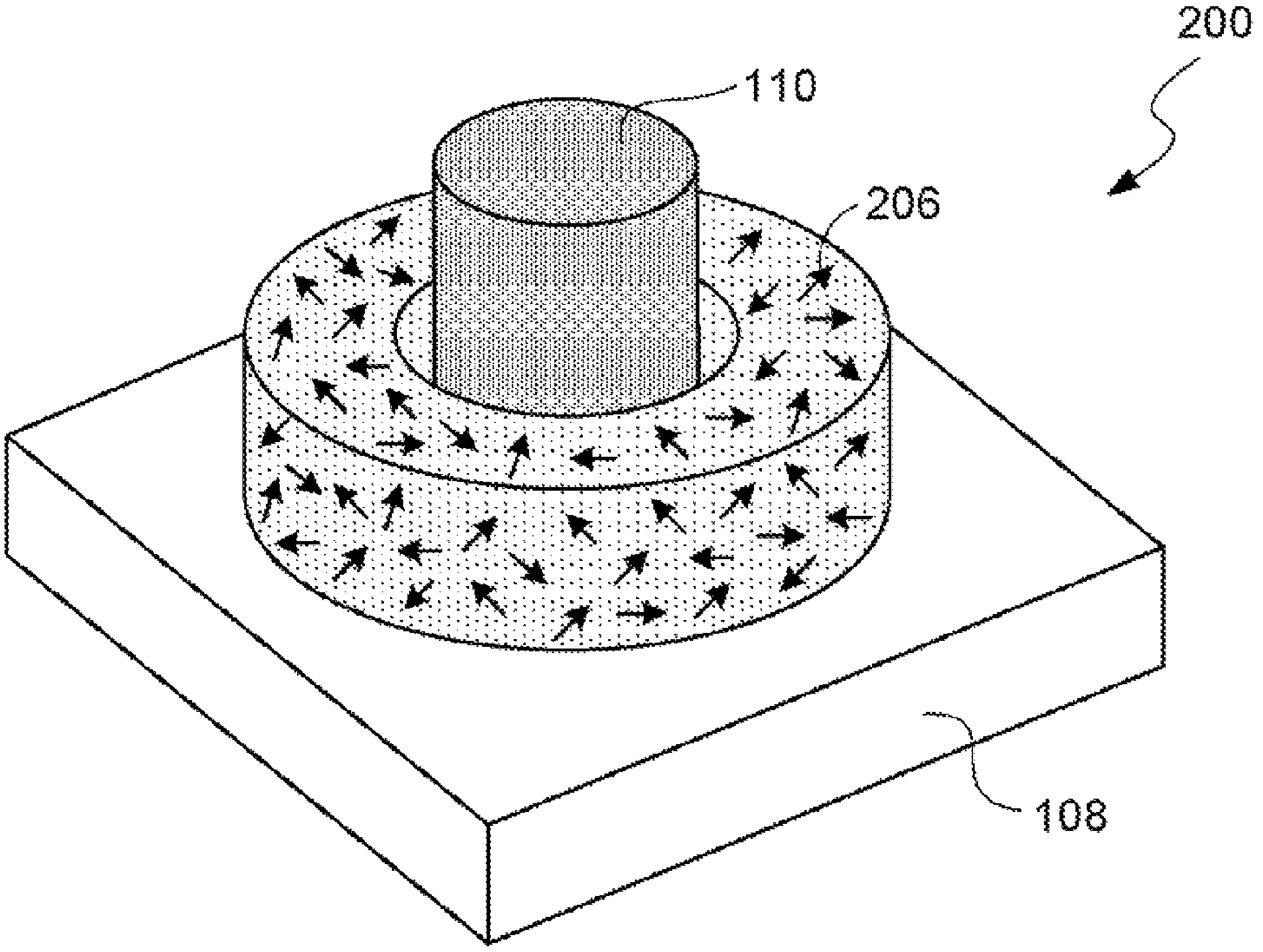
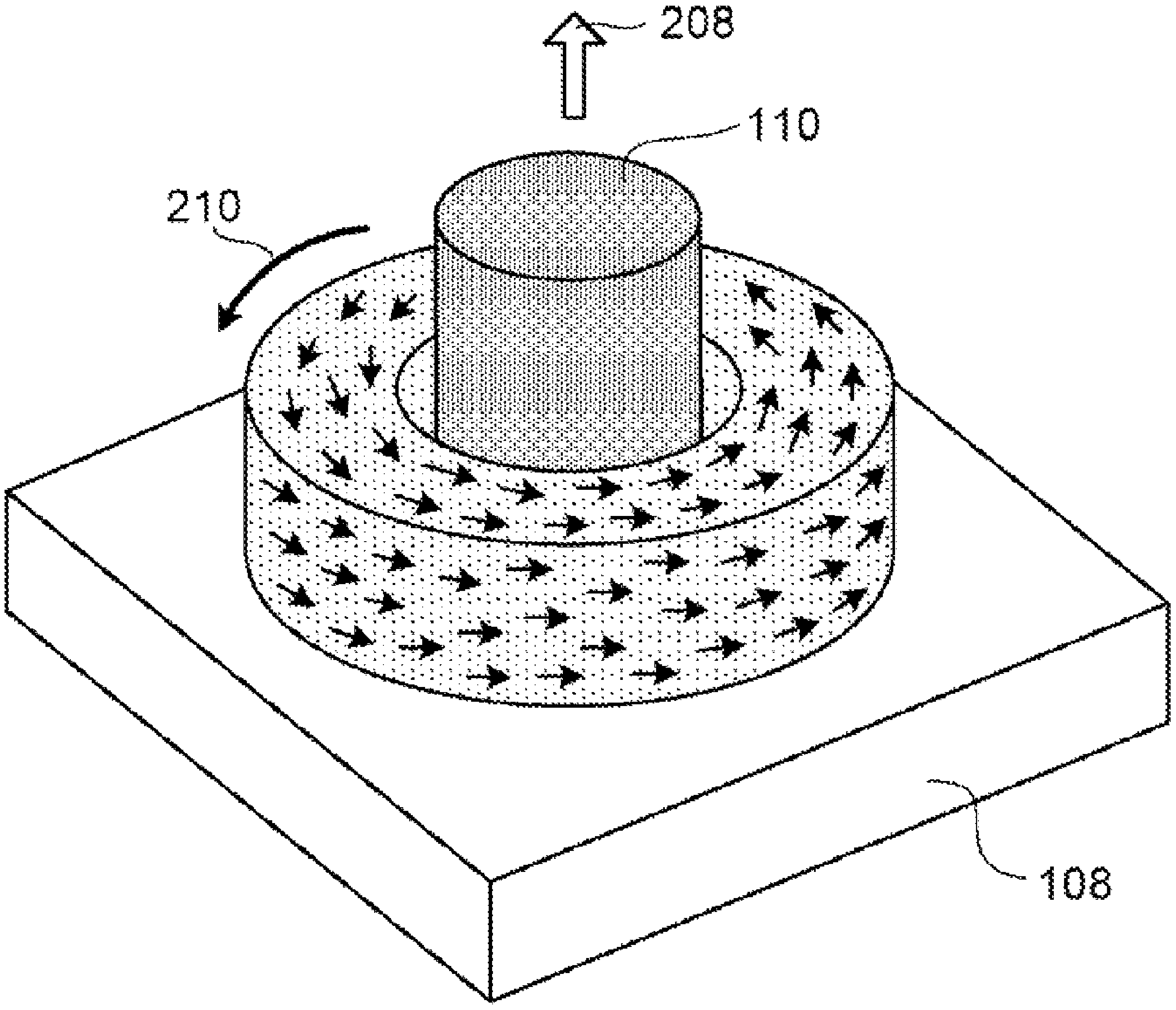


Figure 2C



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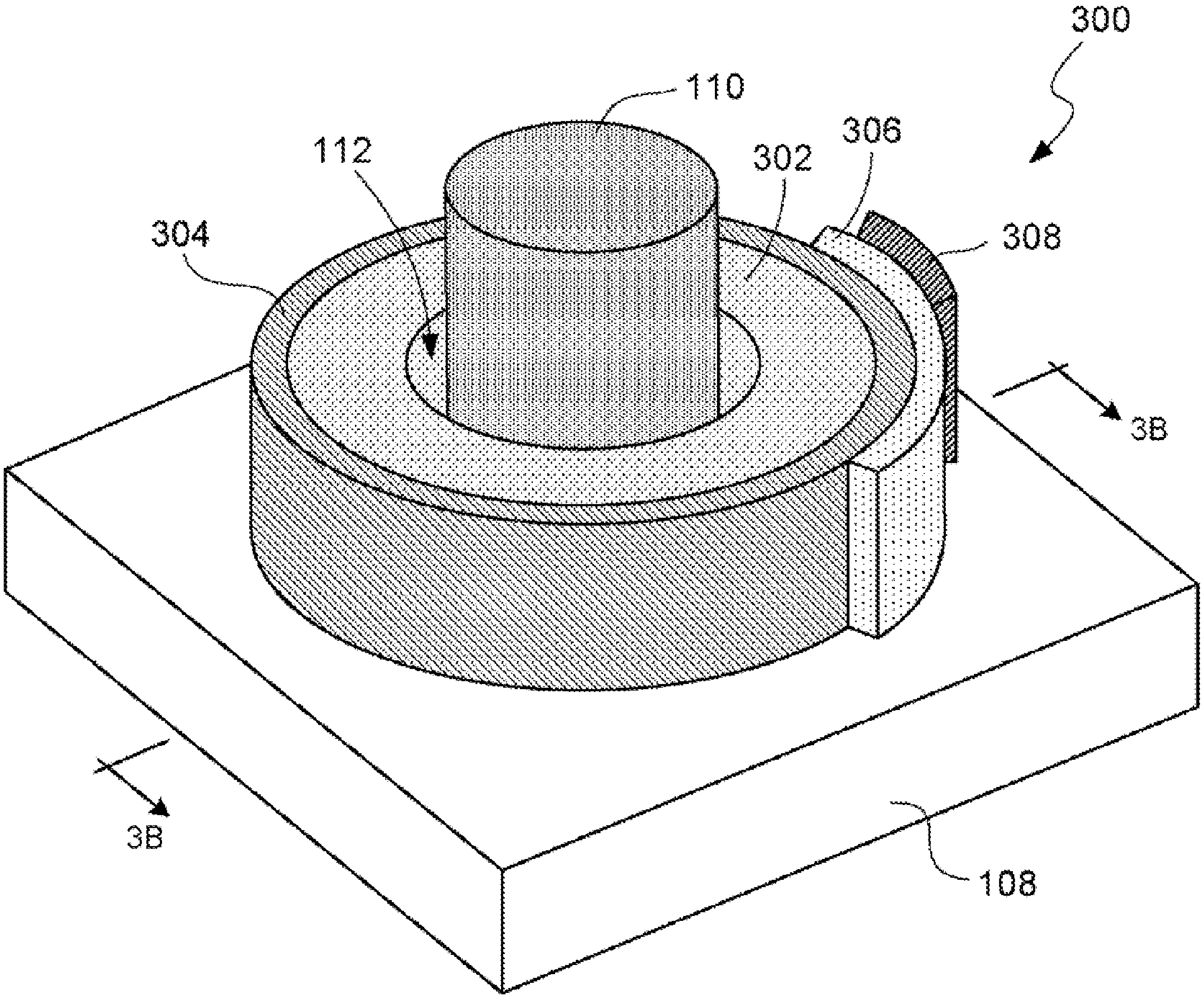
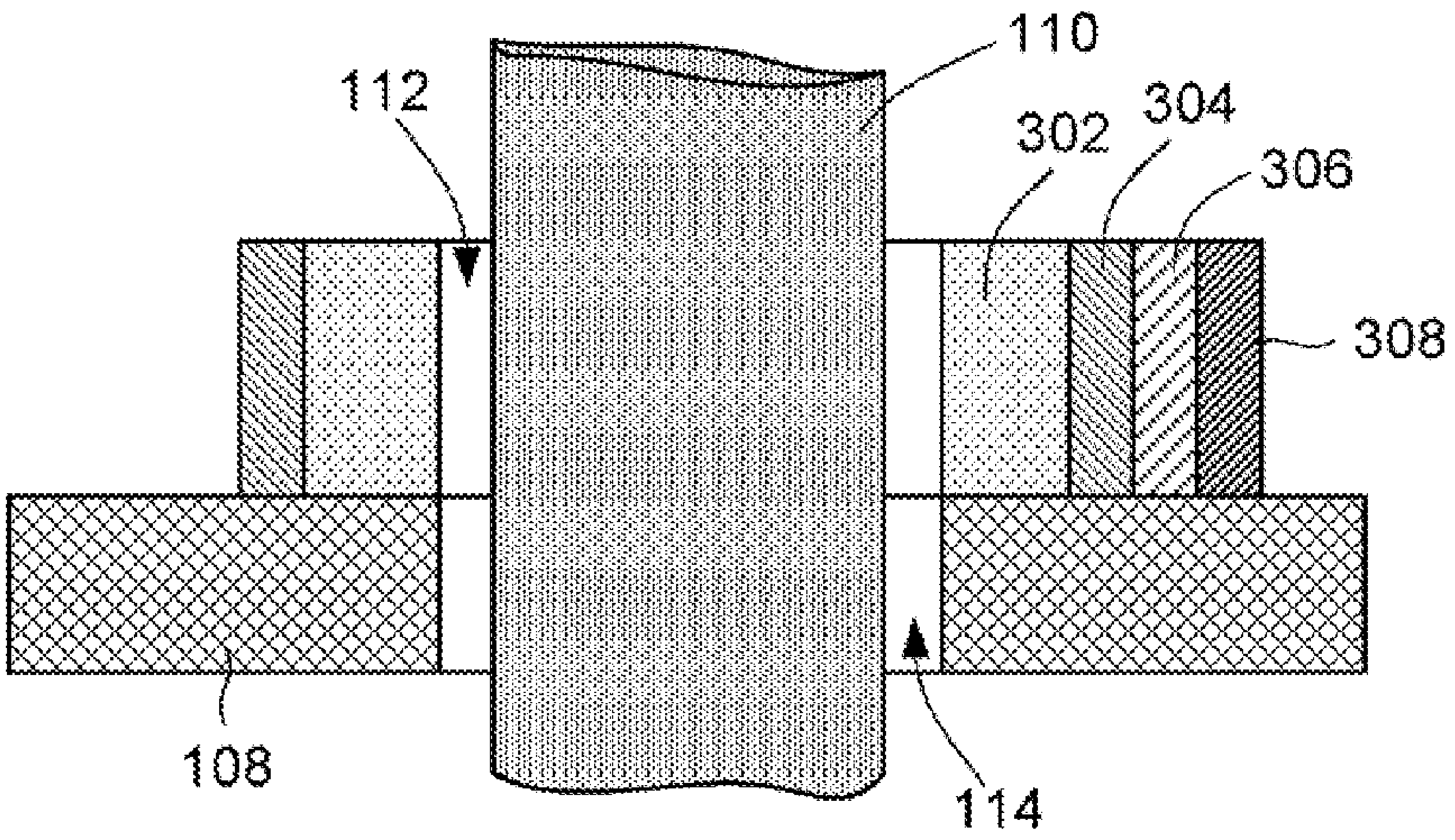


Figure 3A



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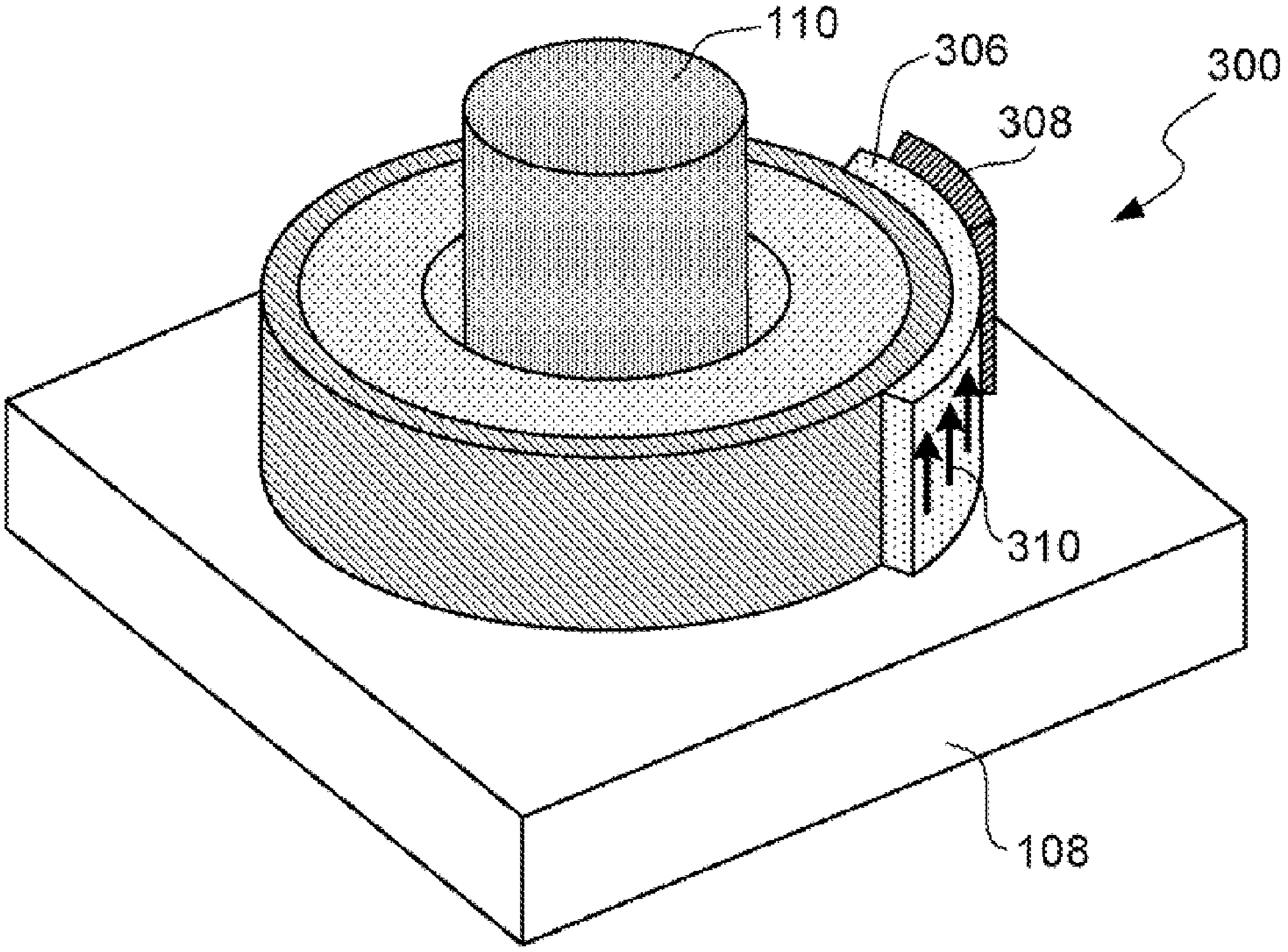

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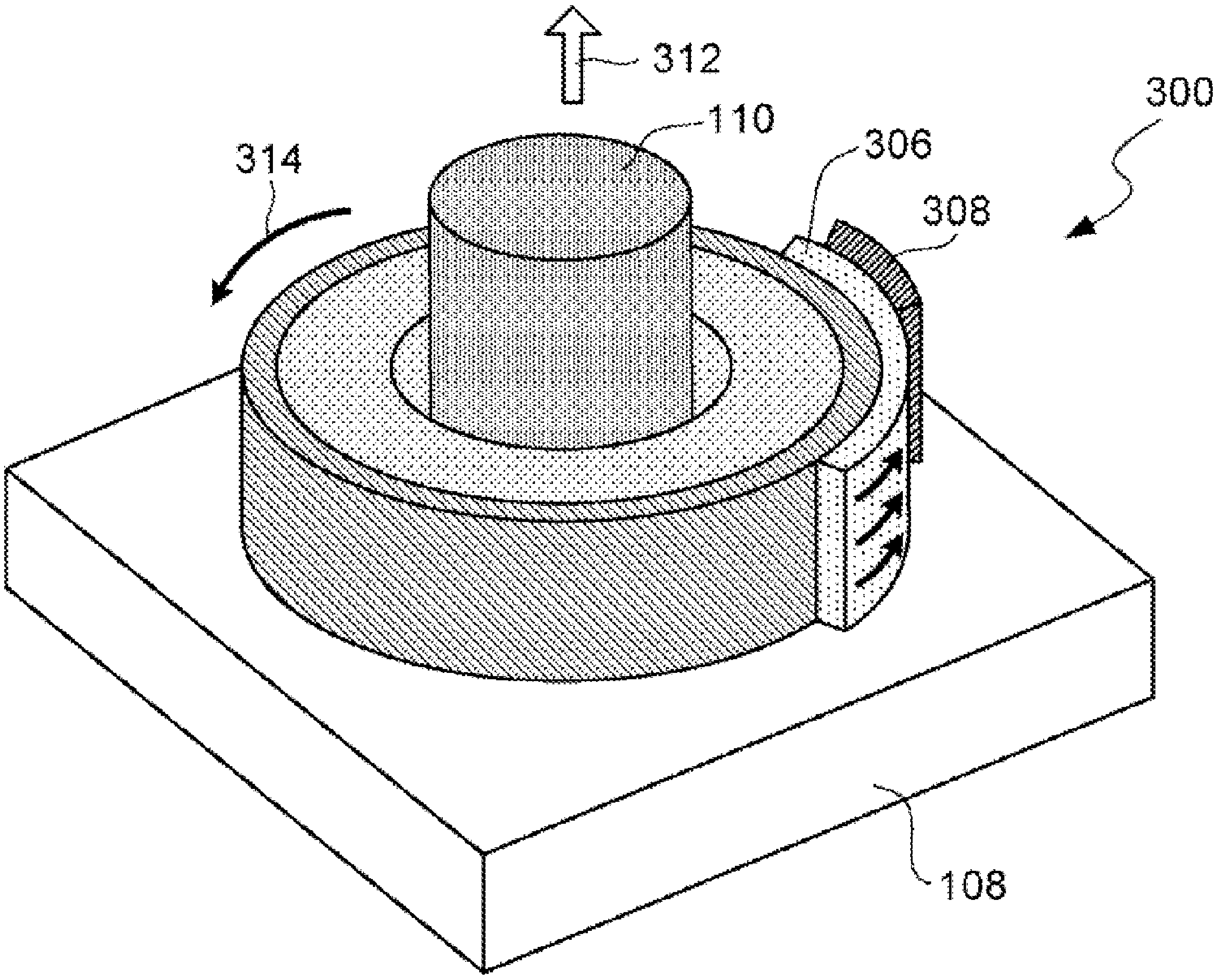

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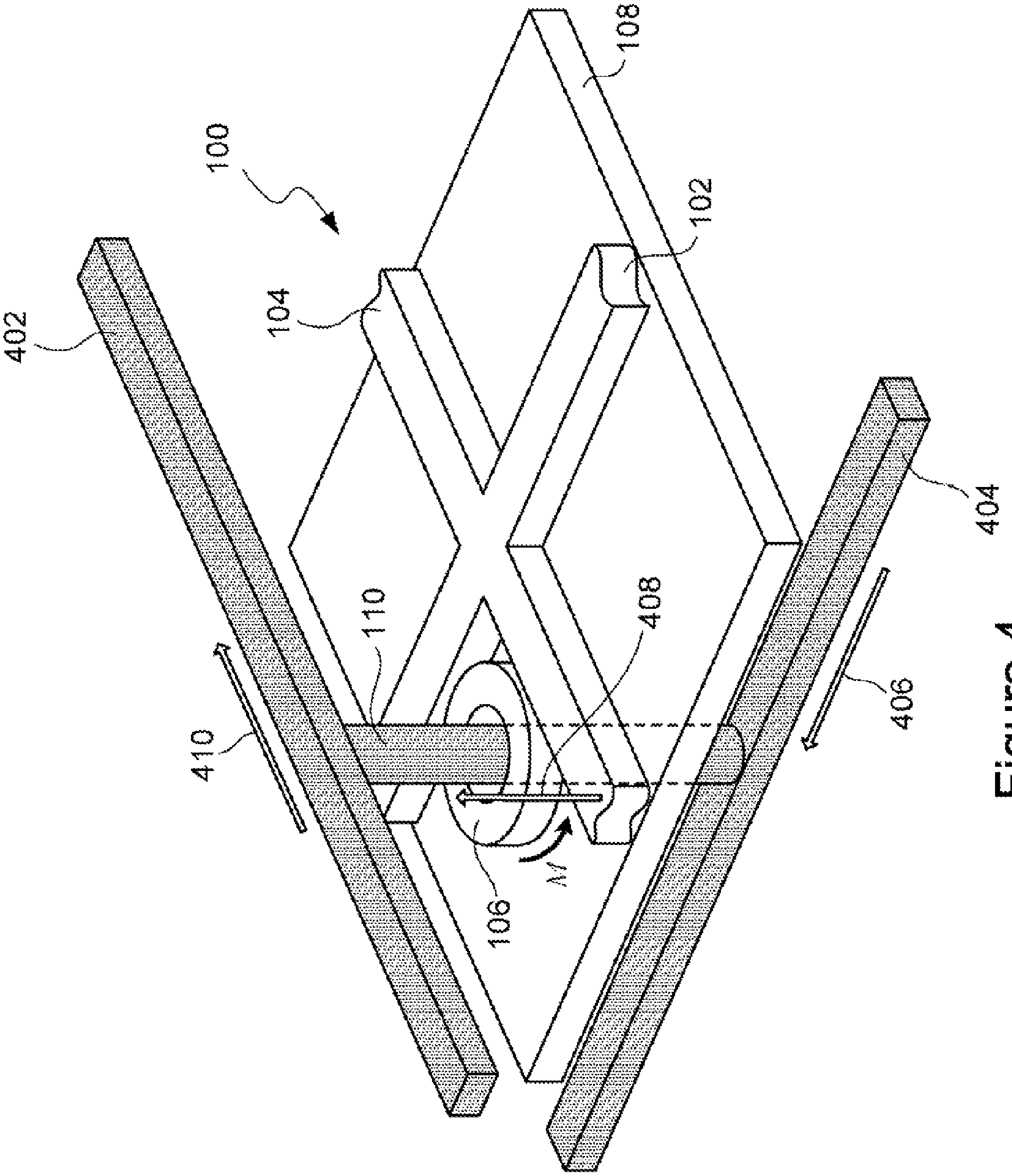
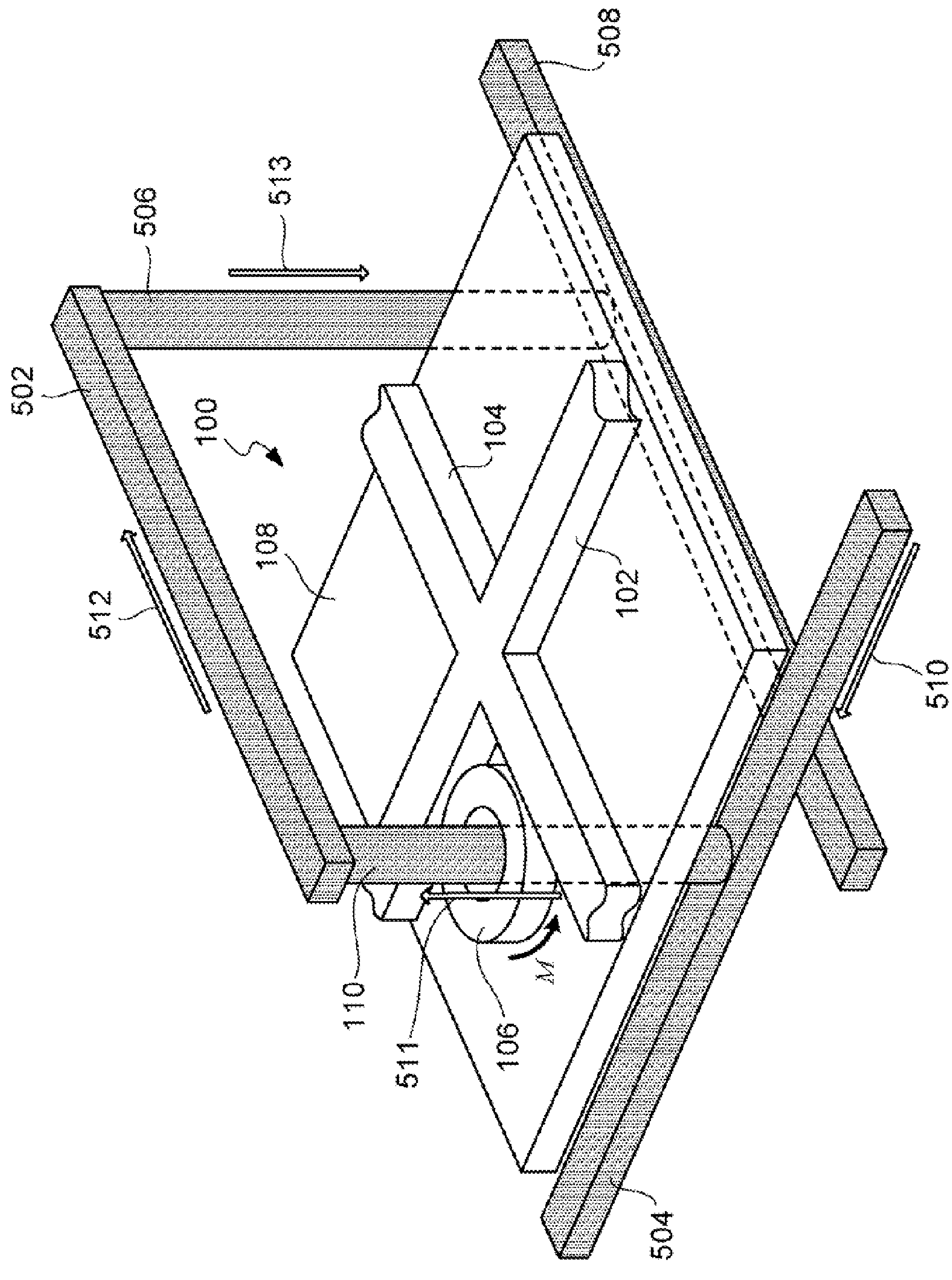


Figure 4



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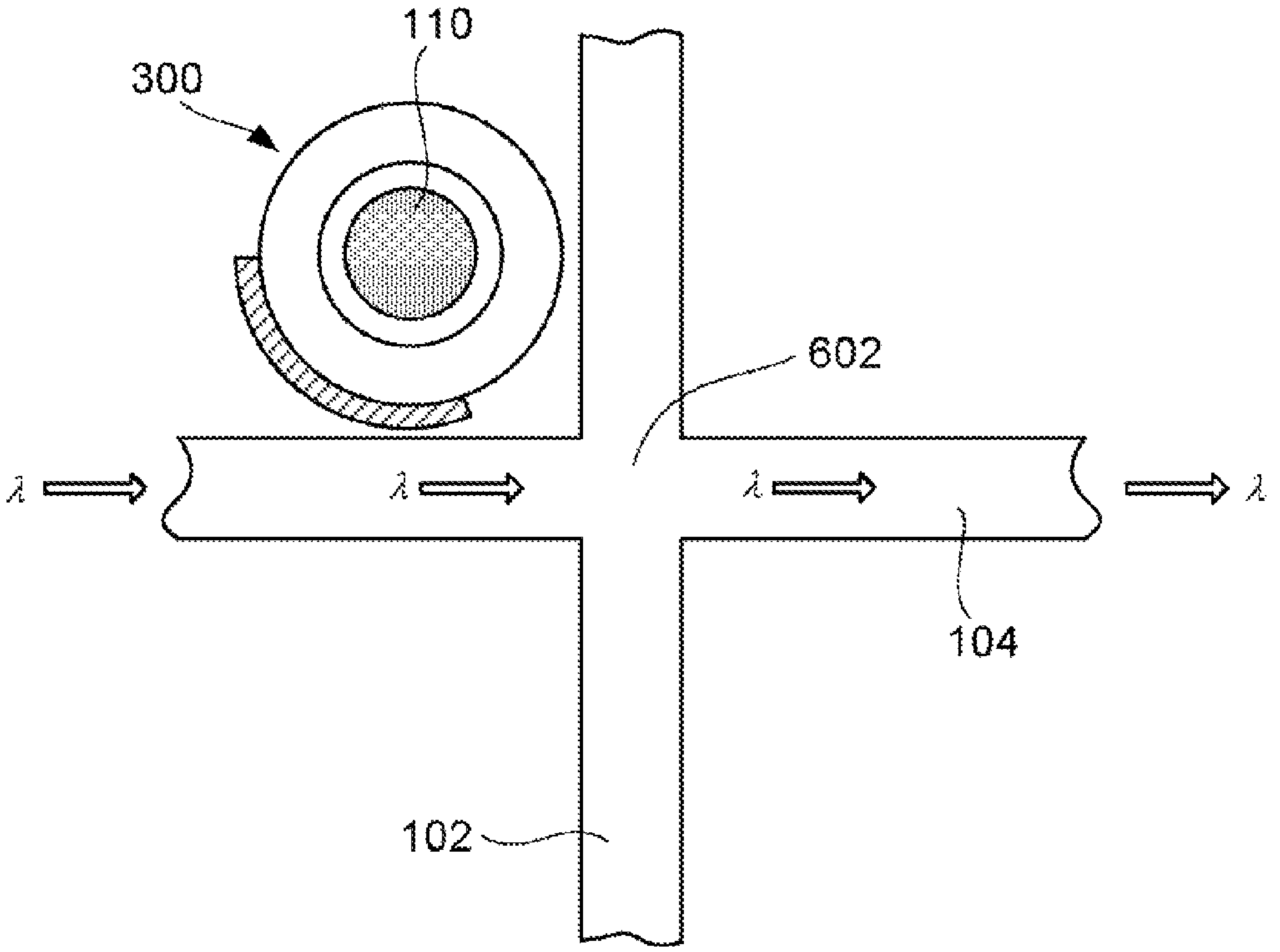
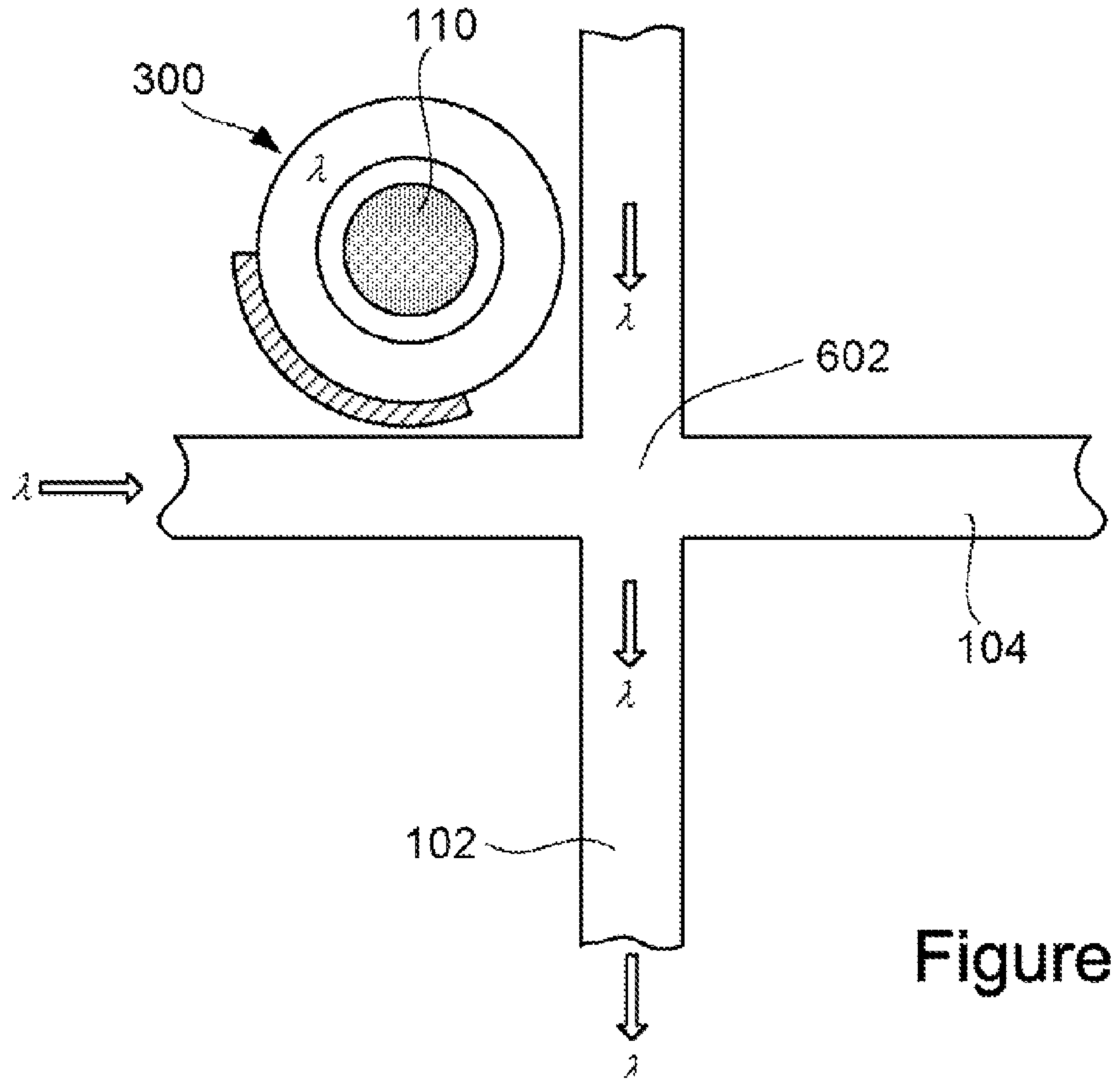


Figure 6A



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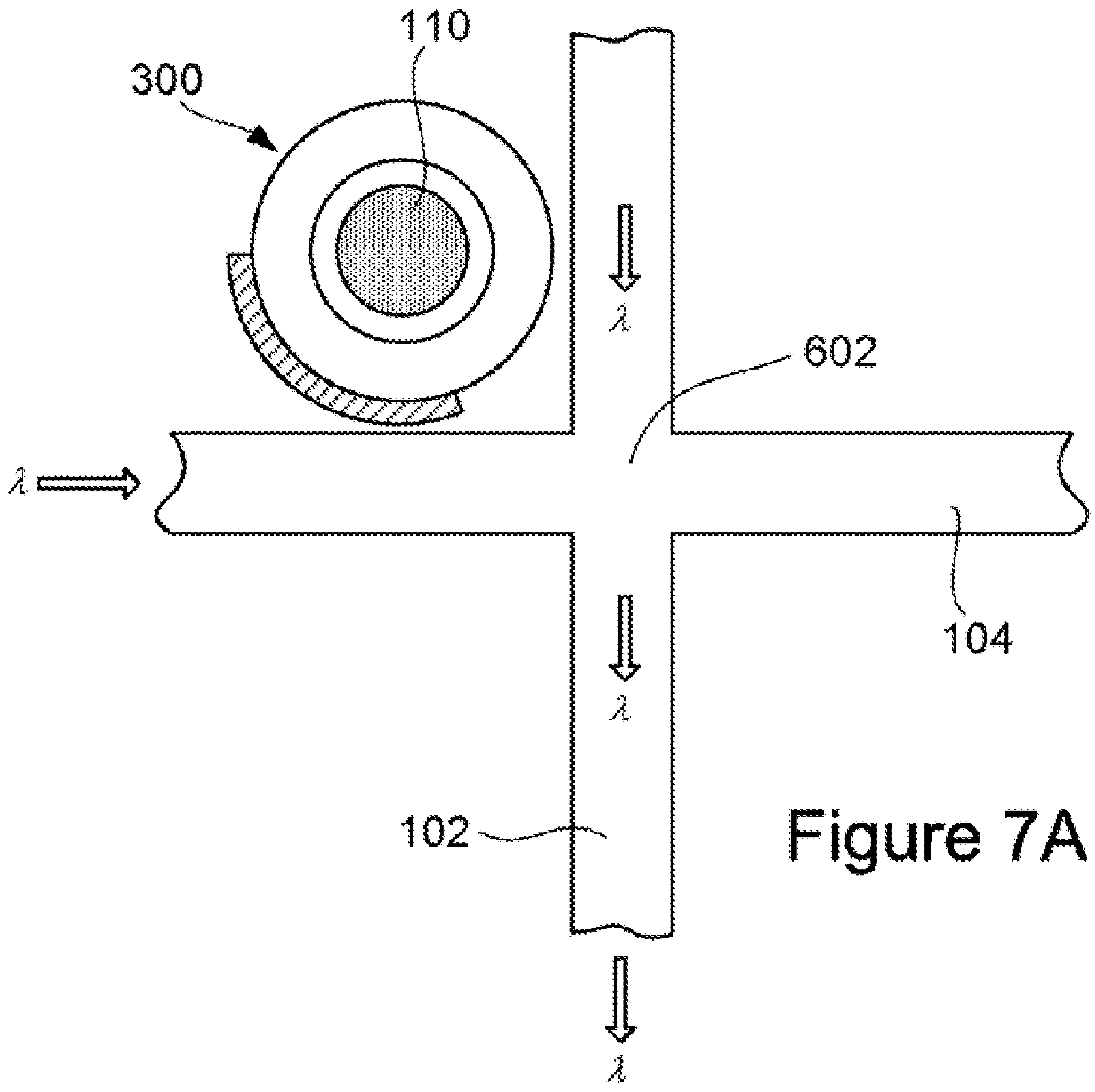

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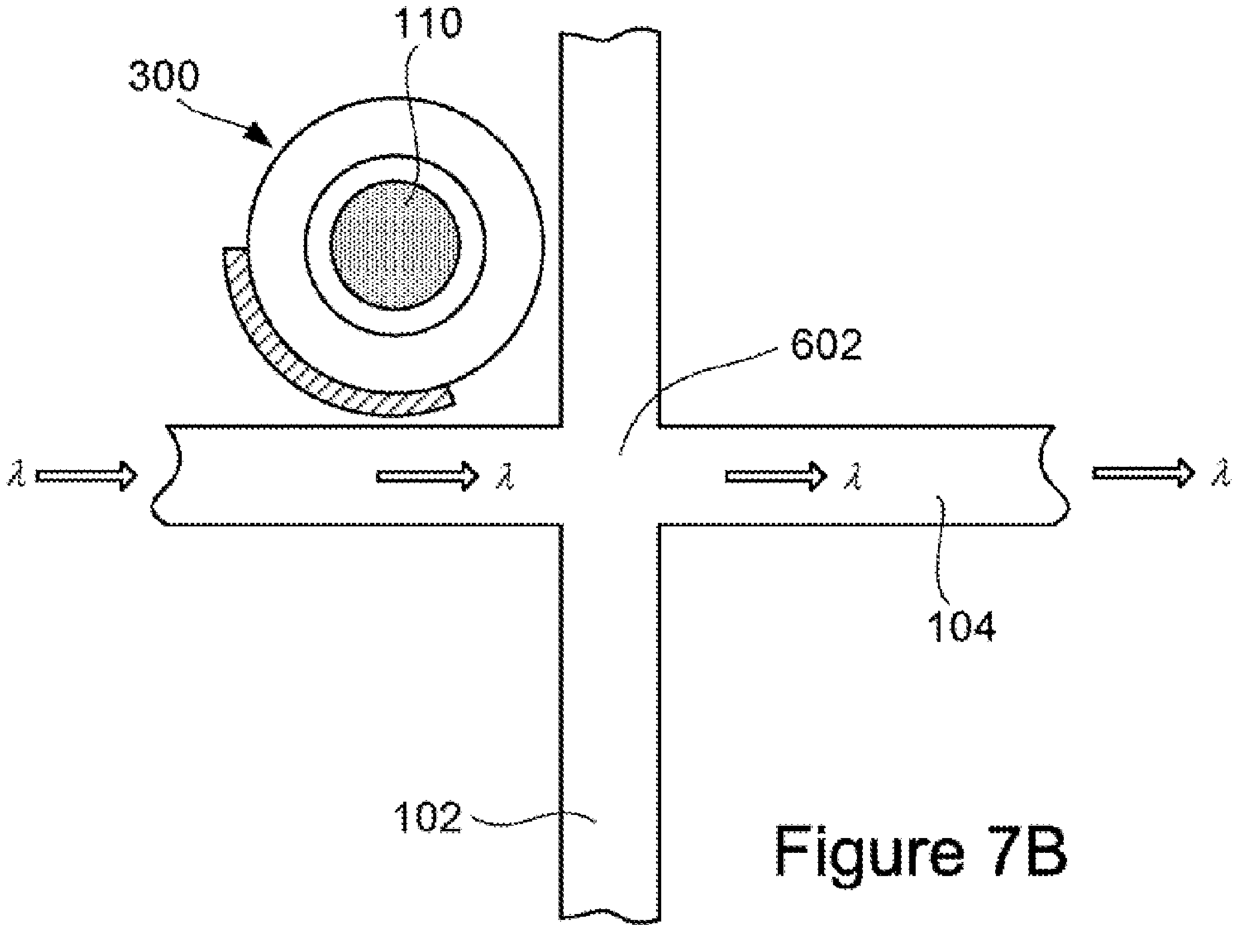

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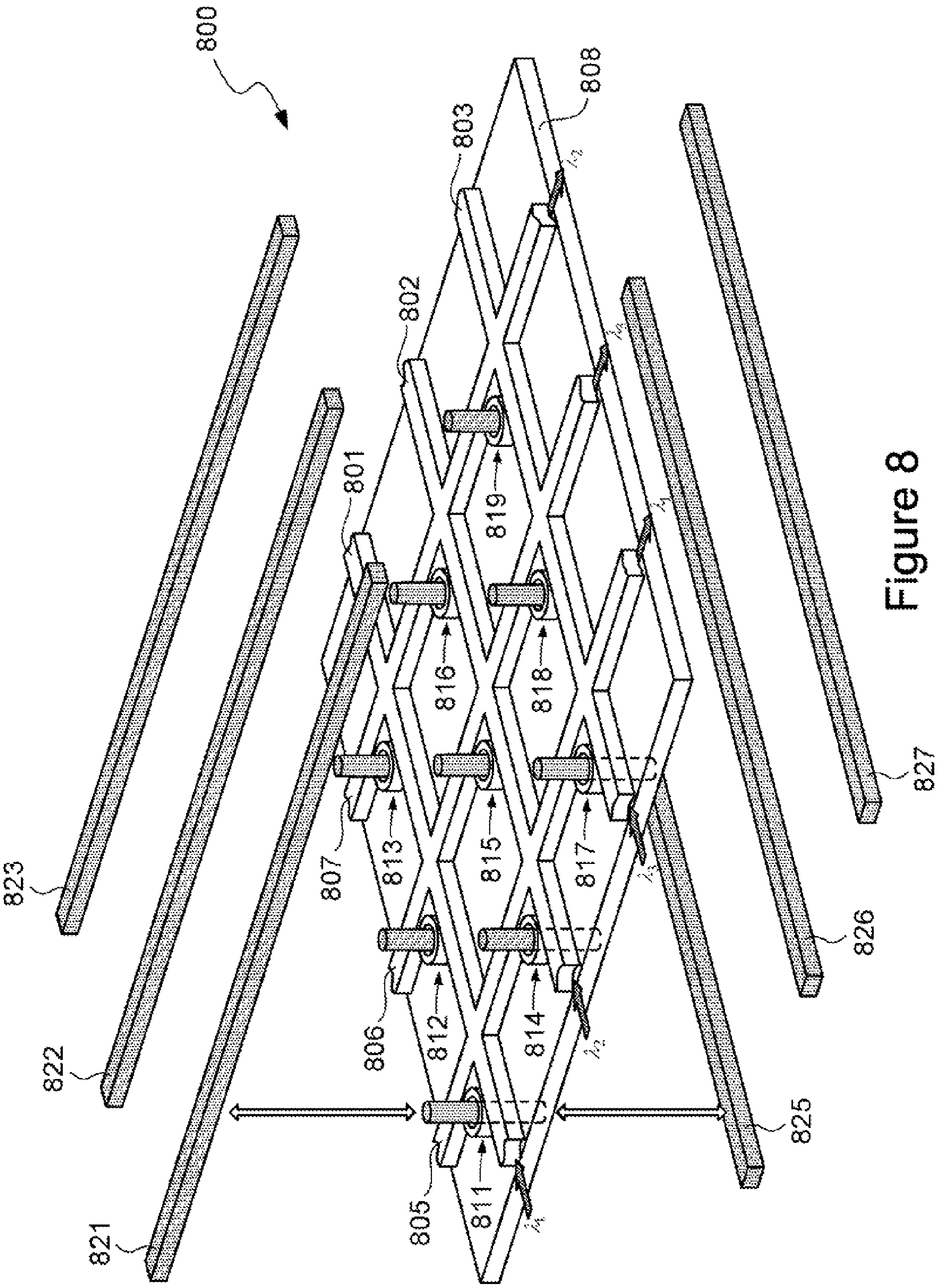
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Figure 8

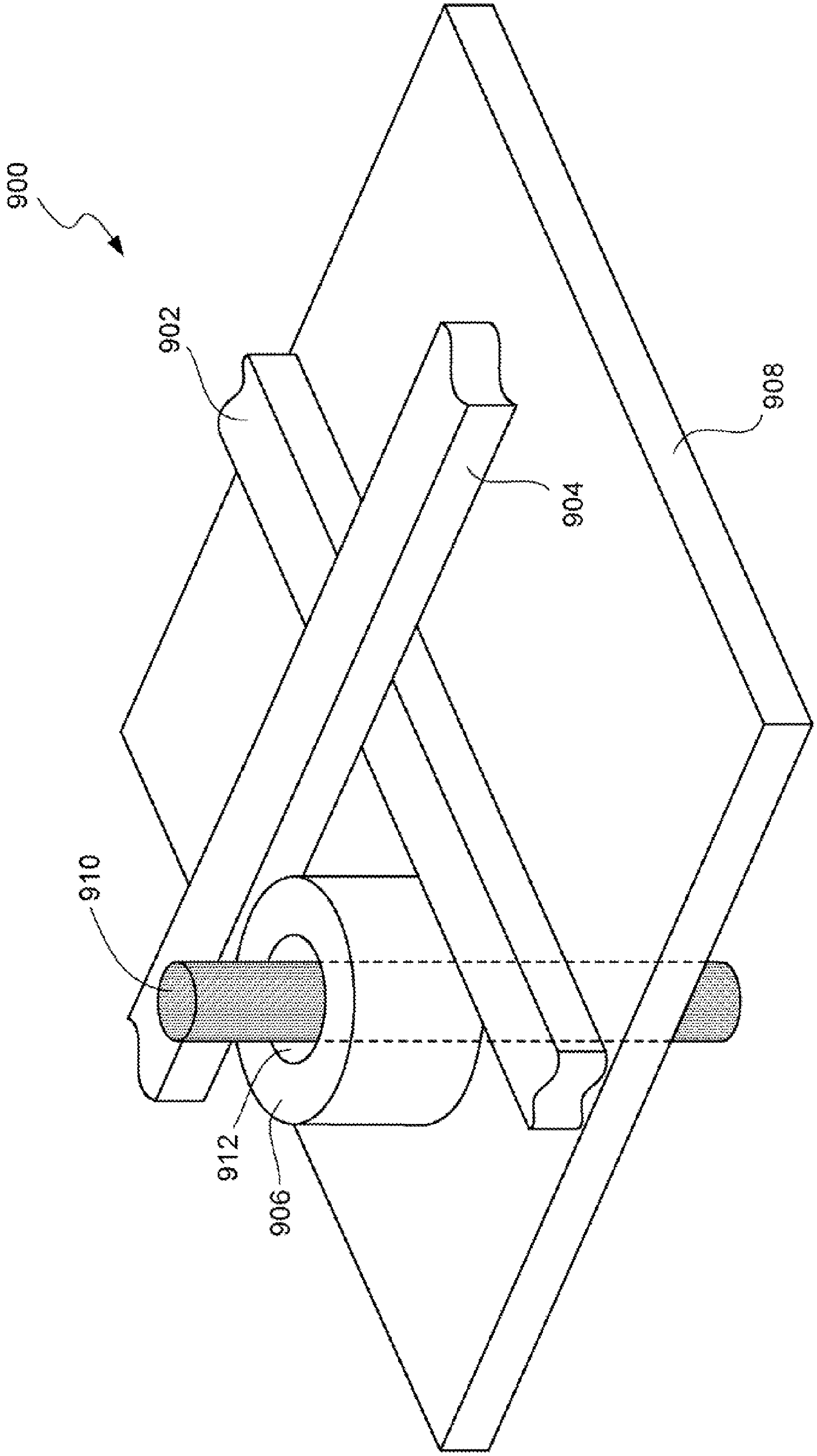

Figure 9

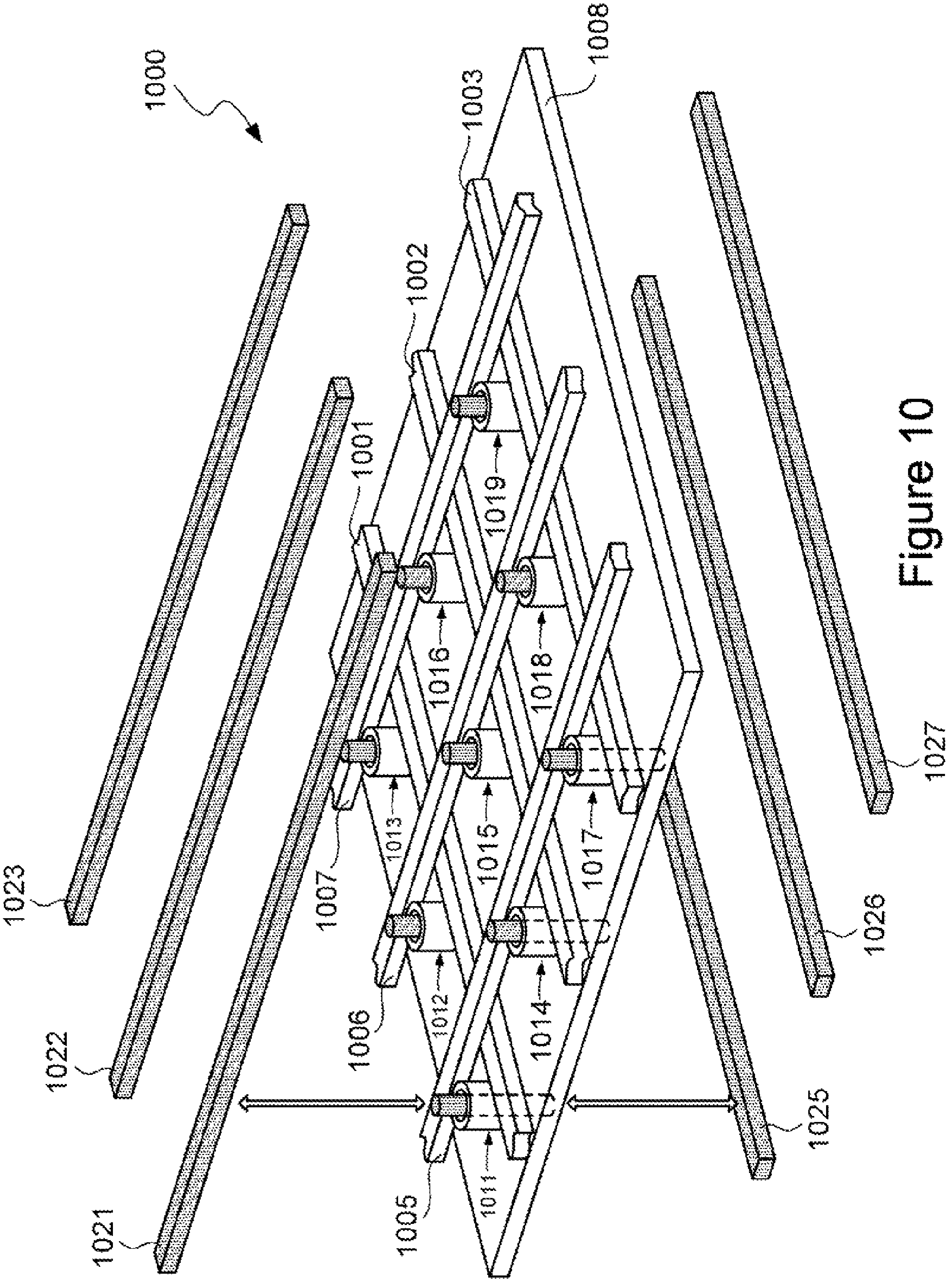
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Figure 10

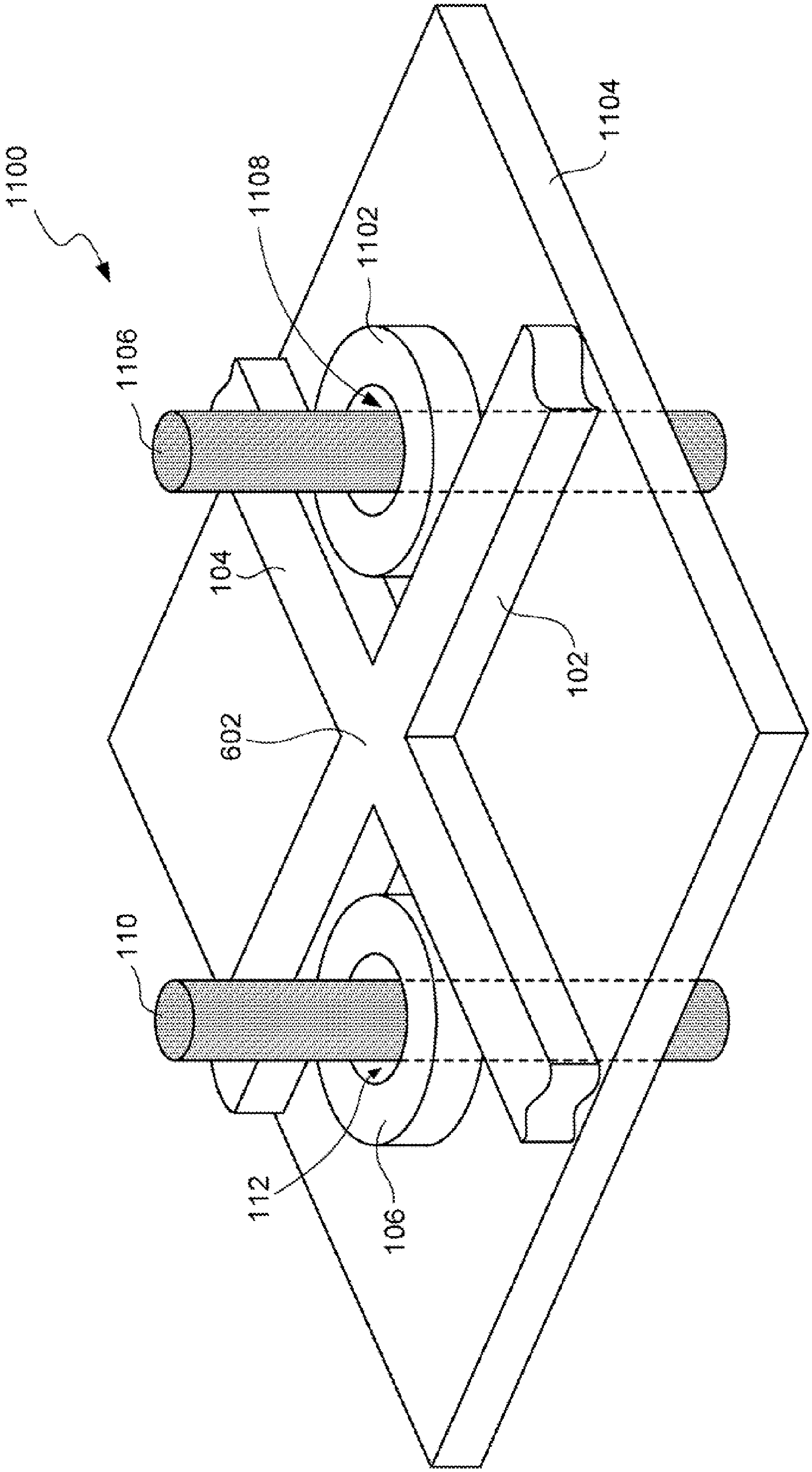

Figure 11

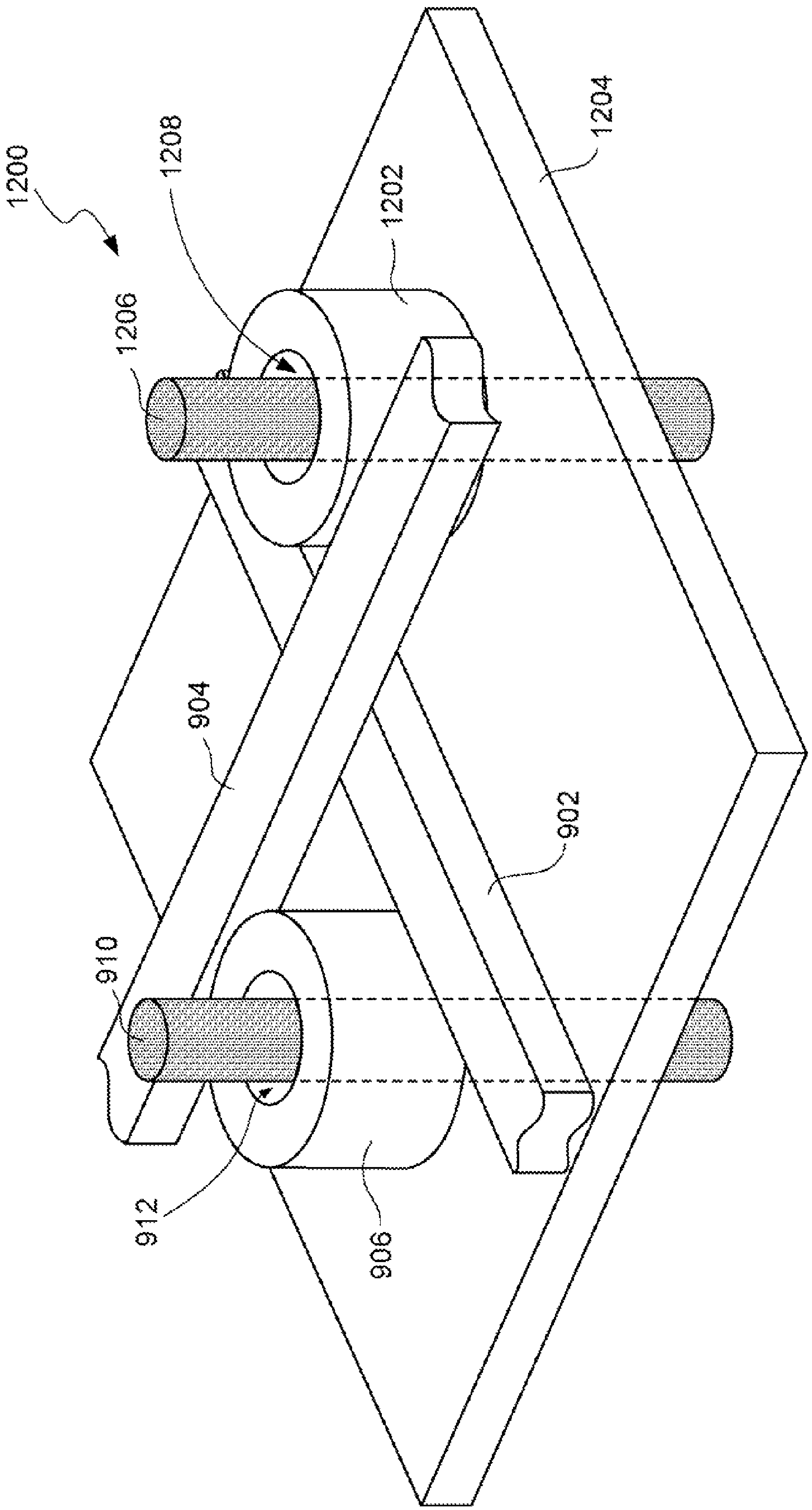

Figure 12

MAGNETICALLY ACTIVATED PHOTONIC SWITCHES AND SWITCH FABRICS EMPLOYING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims priority from provisional application Ser. No. 61/001,471, filed Oct. 31, 2007, the contents of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

Embodiments of the present invention are directed to photonic switches and photonic-switch-based switch fabrics.

BACKGROUND

Switch fabrics are typically employed for "raw" data switching from input ports to output ports of various kinds of devices, including processors, memory, circuit boards, servers, storage servers, external network connections or any other data processing, storing, or transmitting device. However, switch fabrics can often be a data processing bottleneck for many different kinds of computing environments. A typical switch fabric, for example, can limit the scope of a computing environment's ability to handle the ever increasing data processing and transmission needs of many applications, because many switch fabrics are fabricated to accommodate only the "port-rate of the day" and the "port-count of the day" and are not fabricated to accommodate larger bandwidths that may be needed to effectively accommodate future applications. In particular, the amount and frequency with which data is exchanged between certain devices can be larger for some devices than for others, and the use of low-latency, metal-signal lines employed by most switch fabrics also have limited bandwidths. As a result, the amount of data that can be transmitted between devices may not be well matched to the data transfer needs of the devices employed by an application at each point in time, which often results in data processing delays. In addition, the use of signal lines necessitates considerable power consumption in order to transmit electrical signals between devices.

A number of the issues associated with electrical signals transmitted via signal lines can be significantly reduced by encoding the same information in electromagnetic, radiation ("EMR") that is transmitted via waveguides. First, the data transmission rate can be increased significantly due to the much larger bandwidth provided by waveguides. Second, power consumption per transmitted bit is lower for EMR transmitted via waveguides than for transmitting the same data in electrical signals via signal lines. Third, degradation or loss per unit length is much less for EMR transmitted via waveguides than for electrical signals transmitted via signal lines. Physicists and engineers have recognized a need for fast switching devices that can accommodate data encoded EMR as a medium for transmitting massive amounts of data between various kinds of data processing, storing, or transmitting devices.

SUMMARY

Various embodiments of the present invention are directed to photonic switches and switch fabrics employing the photonic switches. In one embodiment of the present invention, a photonic switch comprises a first waveguide disposed on a surface of a substrate in proximity to an opening in the substrate, and a second waveguide crossing the first waveguide and positioned in proximity to the opening in the substrate. The photonic switch includes a tunable microring resonator disposed on the surface of the substrate adjacent to the first waveguide and the second waveguide and configured with an opening aligned with the opening in the substrate. The photonic switch also includes a wire having a first end and a second end and configured to pass through the opening in the microring and the opening in the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A shows an isometric view of a first photonic switch in accordance with embodiments of the present invention.

FIG. **1**B shows an exploded isometric view of the first photonic switch, shown in FIG. **1**A, in accordance with embodiments of the present invention.

FIG. **2**A shows an isometric view of a first tunable microring resonator in accordance with embodiments of the present invention.

FIG. **2**B shows a cross-sectional view of the first tunable microring resonator along a line **2**B-**2**B, shown in FIG. **2**A, in accordance with embodiments of the present invention.

FIGS. **2**C-**2**D show how magnetic moments of the tunable microring resonator, shown in FIGS. **2**A-**2**B, are changed in accordance with embodiments of the present invention.

FIG. **3**A shows an isometric view of a second tunable microring resonator in accordance with embodiments of the present invention.

FIG. **3**B shows a cross-sectional view of the second tunable microring resonator along a line **3**B-**3**B, shown in FIG. **3**A, in accordance with embodiments of the present invention.

FIGS. **3**C-**3**D show how magnetic moments of the microring, shown in FIGS. **3**A-**3**B, are changed in accordance with embodiments of the present invention.

FIG. **4** shows an isometric view of the first photonic switch, shown in FIG. **1**, and attached to a first set of wires in accordance with embodiments of the present invention.

FIG. **5** shows an isometric view of the first photonic switch, shown in FIG. **1**, and attached to a second set of wires in accordance with embodiments of the present invention.

FIGS. **6**A-**6**B show a first operation of the first photonic switch, shown in FIG. **1**, in accordance with embodiments of the present invention.

FIGS. **7**A-**7**B show a second operation of the first photonic switch, shown in FIG. **1**, in accordance with embodiments of the present invention.

FIG. **8** shows an exploded isometric view of a first switch fabric in accordance with embodiments of the present invention.

FIG. **9** shows an isometric view of a second photonic switch in accordance with embodiments of the present invention.

FIG. **10** shows an exploded isometric view of a second switch fabric in accordance with embodiments of the present invention.

FIG. **11** shows an isometric view of a third photonic switch in accordance with embodiments of the present invention.

FIG. **12** shows an isometric view of a fourth photonic switch in accordance with embodiments of the present invention.

DETAILED DESCRIPTION

Embodiments of the present invention are directed to photonic switches and to switch fabrics employing the same photonic switches. These embodiments employ at least one microring resonator having resonance frequencies that are tunable by inducing a local, solenoidal magnetic field within the microrings. The magnetic field can be induced by passing a current through a wire running through the microring opening. A magneto-optical effect causes circular birefringence within the microrings. In other words, a different phase velocity exists for EMR waves with opposite circular polarizations circulating within the microrings. The circulating EMR ways can be considered to recombine upon emergence from the magnetized microring but with a net phase offset, resulting in a rotation of the angle of linear polarization. Unlike conventional electronic switches and switch fabrics, photonic switches and switch fabrics of the present invention consume less power, provide a higher bandwidth, and do not suffer from substantial loss over longer distances.

In the following description, the terms “photonic” and “photonically” refer to devices that operate with classical and/or quantized EMR having wavelengths that are not limited to just the visible portion of the electromagnetic spectrum. In the various photonic switch and switch fabric embodiments described below, a number of structurally similar components comprising the same materials have been provided with the same reference numerals and, in the interest of brevity, an explanation of their structure and function is not repeated.

FIG. **1**A shows an isometric view of a first photonic switch **100** in accordance with embodiments of the present invention. The photonic switch **100** includes a first ridge waveguide **102**, a second ridge waveguide **104** intersecting the first waveguide **102**, and a tunable microring resonator (“microring”) **106**, all of which are disposed on a surface of a substrate **108**. The photonic switch **100** also includes a wire **110** passing through an opening **112** in the microring **106** and an opening (not shown) in the substrate **108**. FIG. **1**B shows an exploded isometric view of the photonic switch **100** with the first and second waveguides **102** and **104** and the microring **106** lifted above the substrate **108** in accordance with embodiments of the present invention. FIG. **1**B reveals an opening **114** through the substrate **108** in approximate alignment with the opening **112** in the microring **106**. The openings **112** and **114** allow the wire **110** to pass through the substrate **108** and the microring **106**. The wire **110** extends approximately perpendicular to the substrate **108**.

The waveguides **102** and **104** can be comprised of a column IV semiconductor, such as Si and Ge, or a compound III-V semiconductor, where Roman numerals III and V refer to elements in the third and fifth columns of the Periodic Table of the Elements. Examples of suitable compound III-V semiconductors are InP, InAs, GaP, GaN, GaAs, and $In_xGa_{1-x}As_yP_{1-y}$, where the parameters x and y can range between 0 and 1. The choice of composition x and y are well-known in the art. The waveguides can be comprised of other suitable material having a refractive index that is greater than the substrate **108**. The substrate **108** can be comprised of a material having a lower refractive index than the waveguides **102** and **104**. For example, the substrate **108** can be comprised of SiO_2, Si_3N_4, Al_2O_3, or another suitable dielectric insulating material. The combination of materials selected for the substrate **108** and the waveguides **102** and **104** may depend on matching the lattice constant of the materials selected for the waveguides **102** and **104** with the lattice constant of the materials selected for the substrate **108**. The wire **110** can be comprised of silver, gold, copper, nickel, chromium, platinum, aluminum, an alloy thereof, or any other suitable conductor.

Although the wire **110** shown in FIG. **1** has a circular cross-section, embodiments of the present invention are not so limited. The wire **110** can also have square, rectangular, elliptical, or more complex cross sections. The wire **110** may also have many different widths or diameters and aspect ratios or eccentricities, and the wire **110** may have nanoscale to microscale cross-sectional dimensions. For example, the diameter of the wire **110** may range from about 1-2 microns. The waveguides **102** and **104** can be single-mode waveguides with cross-sectional dimensions ranging from about 400-600 nm in width by about 150-450 nm in height. Preferably, these cross-sectional dimensions can be about 500 nm in width by about 250 nm in height, but these dimensions can vary depending on the implementation. Although the intersecting waveguides **102** and **104** appear in FIG. **1** to intersect at about 90°, in other embodiments, the waveguides **102** and **104** can intersect at angles other than 90°, such as angles ranging from about 45° to about 90°. The microring may have an outer diameter of about 7-15 microns and an inner diameter as large as about 10 microns.

The microring **106** shown in FIG. **1** represents many different kinds of suitable microrings that can be used in the photonic switch **100**. In other words, the microring **106** can actually be comprised of a number of different materials and components, two of which are described below with reference to FIGS. **2** and **3**.

FIG. **2**A shows an isometric view of a first tunable microring resonator **200** disposed on a portion of the substrate **108** in accordance with embodiments of the present invention. As shown in FIG. **2**A, a portion of the wire **110** passes through the opening **112**. FIG. **2**B shows a cross-sectional view of the microring **200** along a line **2**B-**2**B, shown in FIG. **2**A, in accordance with embodiments of the present invention. The wire **110** passes through the opening **112** in the microring **200** and the opening **114** in the substrate **108**. FIG. **2**B also reveals that the microring **200** includes an inner microring **202** disposed on a surface of the substrate **108**. At least a portion of the outer surface of the inner microring **202** is covered with a magnetic material **204**. The inner microring **202** can be comprised of a column IV semiconductor or a compound III-V semiconductor, such as InP, InAs, GaP, GaN, GaAs, or $In_xGa_{1-x}As_yP_{1-y}$, as described above with reference to the waveguides **102** and **104**. The inner microring **202** can be doped with suitable paramagnetic impurities, such as Mn, Or, Ni, Fe, Co, alloys thereof, rare earth ions, like terbium. The inner microring **202** can also be comprised of commonly used materials for the 700-1100 nm wavelength range, such as terbium doped borosilicate glass and terbium gallium garnet crystal ($Tb_3Ga_5O_{12}$) that have the largest Faraday rotation angles. The magnetic material **204** coats at least a portion of the outer surface of the inner microring **202** and can be comprised of a “soft” ferromagnetic material, such as Ni, Fe, permalloy, which contains about 20% Fe and about 80% Ni and has a very small coercive field, or another suitable ferromagnetic material.

FIGS. **2**C-**2**D show how magnetic moments of the materials comprising the microring **200** are changed when a current is applied to the wire **110** in accordance with embodiments of the present invention. The magnetic moments are represented by directional arrows, such as directional arrow **206**. In FIG. **2**C, when no current is applied to the wire **110**, the magnetic moments are randomly oriented. However, when a current **208** is applied to the wire **110**, as shown in FIG. **2**D, the magnetic moments are aligned with the direction of the solenoidal magnetic field **210** induced by the current in the wire **110**.

FIG. **3**A shows an isometric view of a second tunable microring resonator **300** disposed on a portion of the substrate **108** in accordance with embodiments of the present invention. The wire **110** passes through the opening **112**. FIG. **3**A also shows that the microring **300** is comprised of an inner microring **302**, an outer microring **304**, and a segment **306**. FIG. **3**B shows a cross-sectional view of the microring **300** along a line 3B-3B, shown in FIG. **3**A, in accordance with embodiments of the present invention. The wire **110** passes through the opening **112** in the microring **300** and the opening **114** in the substrate **108**. FIGS. **3**A-**3**B also reveal a segment **306** covering a portion of the outer surface of the outer microring **304** and a pinning stub **308** attached to at least a portion of the outer surface of the segment **306**. The inner microring **302** can be comprised of an intrinsic column IV semiconductor, such as Si or Ge, or an intrinsic compound III-V semiconductor, such as GaN or $In_xGa_{1-x}As_yP_{1-y}$, as described above. The outer microring **304** can be comprised of SiO_2, Al_2O_3, Si_3N_4, or another suitable dielectric material. The segment **306** covering a portion of the outer microring **304** can be comprised of a ferromagnetic material, such as Ni, Fe, permalloy, or another suitable ferromagnetic materials. The pinning stub **308** can be comprised of an antiferromagnetic material, such as FeMn, NiO, Cr_2O_3, or another suitable antiferromagnetic material.

FIGS. **3**C-**3**D show how magnetic moments of the segment **306** are changed when a current is applied to the wire **110** in accordance with embodiments of the present invention. The pinning stub **308** can be deposited and positioned on the segment **306** in order to align the magnetic moments of the segment **306** into a particular direction. For example, as shown in FIG. **3**C, when no current is applied to the wire **110**, the magnetic moments of the segment **306** can be oriented in the direction represented by the directional arrows, such as directional arrow **310**. However, when a current **312** is applied to the wire **110**, as shown in FIG. **3**D, the magnetic moments of the segment **306** are aligned with the direction of the solenoidal magnetic field circulating in the direction **314** is created.

The microrings **200** and **300** have resonance frequencies that can be tuned by interaction of the corresponding circular-microring modes with the local magnetization induced or changed by the solenoid magnetic field created by the current flowing through the wire **110**. The microrings **200** and **300** use a magneto-optical effect to evanescently couple EMR to and from the waveguides **102** and **104**. The resonance frequencies of the microrings **200** and **300** cause EMR waves to be decomposed into two circularly polarized waves which propagate at different speeds. For example, EMR waves that are circulating within the microrings **200** and **300** with opposite circular polarizations have different phase velocities when the solenoidal magnetic field is created. These waves recombine upon emergence from the microrings **200** and **300**. However, because of the difference in propagation speed they emerge with a net phase difference, resulting in a rotation of the angle of linear polarization. The resonance frequency or wavelength supported by the microrings **200** and **300** shifts. Thus, the current applied to the wire **110** can be used to actively control evanescent coupling of EMR between the waveguides **102** and **104** and the microrings **200** and **300**.

The photonic switch **100** is operated by applying an appropriate current or voltage to the wire **110**. This can be accomplished by attaching a wire to each end of the wire **110** as described below with reference to FIGS. **4** and **5**.

FIG. **4** shows an isometric view of the photonic switch **100** and wires **402** and **404** attached to the ends of the wire **110** in accordance with embodiments of the present invention. Although the wires **402** and **404** appear to be perpendicular to one another and horizontal to the plane of the substrate **108**, the wires **402** and **404** can be arranged in any suitable configuration for supplying current or voltage to the wire **110**. As shown in FIG. **4**, the flow of current through the wires **404**, **110**, and **402** is represented by directional arrows **406**, **408**, and **410**. The current flows from the wire **404** into the wire **110** and out along the wire **402**. In other embodiments, the current can of course be reversed.

FIG. **5** shows a second isometric view of the photonic switch **100** and wires **502** and **504** attached to the ends of the wire **110** in accordance with embodiments of the present invention. As shown in FIG. **5**, the wire **502** is also attached to a third wire **506** which, in turn, is attached to a fourth wire **508** that passes under the wire **504**. The current flows from the wire **504** into the wire **110** and from the wire **110** to the wire **502** as indicated by directional arrows **510**-**512**. The current then flows from the wire **506** and out through the wire **508** as indicated by directional arrow **513**.

An appropriate current applied to the wire **110**, as shown in FIGS. **4** and **5**, generates a magnetic field of magnitude M in the adjacent microring **106**. This magnetic field shifts the resonance of the microring **106** such that a substantially portion of the EMR transmitted in one of the intersecting waveguides can be coupled into the other. In other words, depending on how the microring **106** is configured, the magnetic field can be used to determine whether or not the microring **106** is able to support EMR of a particular frequency, ω. The microring **106** can be operated in the photonic switch **100** in two ways. A first way is described below with reference to FIG. **6**, and a second way is described below with reference to FIG. **7**.

FIGS. **6**A-**6**B show top views of the photonic switch **100** operated in a first way in accordance with embodiments of the present invention. In certain embodiments, the materials and dimensions of the microring **300** can be selected such that the microring **300** does not have resonance with, or cannot support, a channel λ with the frequency ω transmitted along the waveguide **104**. As a result, after inputting the channel λ into the waveguide **104**, as shown in FIG. **6**A, the channel λ passes the microring **300** unaffected, passes through the intersection **602** and out along the remainder of the waveguide **104**, as shown in FIG. **6**A. Note that some loss of the channel λ intensity may occur at the intersection **602**. This loss may occur as a result of a portion of the channel λ spilling over into the intersecting waveguide **102** due to diffraction at the corners of the intersection **602**. This spillover occurs in both directions of the waveguide **102**, but the intensity of the EMR entering the intersecting waveguide **102** is insignificant when compared to the intensity of the channel λ that continues to propagate along the waveguide **104**.

Next, as shown in FIG. **6**B, applying an appropriate current to the wire **110**, as described above with reference to FIGS. **4** and **5**, generates a magnetic field around the microring **300**. This magnetic field shifts the resonance of the microring **300** into resonance with the frequency ω of the channel λ transmitted along the waveguide **104**. As a result, a substantial portion of the channel λ propagating along the waveguide **104** can be evanescently couple into the microring **300**, circulate within the microring **300**, and evanescently couple from the microring **300** into the intersecting waveguide **102**. The channel λ then propagates along the waveguide **102**. Here, loss of the channel λ intensity may occur as a result of a portion of the channel λ not evanescently coupling into the microring **300** and continuing to propagate along the waveguide **104**, and loss may occur again at the intersection **602**.

FIGS. **7**A-**7**B show top views of the photonic switch **100** operated in a second way in accordance with embodiments of the present invention. In other embodiments, the materials and dimensions of the microring **300** can be selected so that the microring **300** has resonance with the frequency ω of the channel λ without generating the magnetic field as described above. As shown in FIG. **7**A, because the microring **300** can support the channel λ, a substantial portion of the channel λ can evanescently couple into the microring **300**, circulate within the microring **300**, and evanescently couple from the microring **300** into the intersecting waveguide **1.02**. The channel λ then propagates along the waveguide **102**. Loss of the channel λ intensity may occur at the intersection **602**, and a portion of the channel λ may not evanescently couple into the microring **300** leaving a portion to propagate along the waveguide **104**.

Next, as shown in FIG. **7**B, applying an appropriate current to the wire **110**, as described above with reference to FIGS. **4** and **5**, generates a magnetic, field around the microring **300**. This magnetic field shifts the resonance of the microring **300** the frequency ω of the channel λ. As a result, the channel λ passes the microring **300** unaffected, passes through the intersection **602** and out along the remainder of the waveguide **104**. As described above, loss of the channel λ intensity may occur at the intersection **602**, but the intensity of the EMR entering the intersecting waveguide **102** is not significant when compared to the intensity of the channel λ that continues to propagate along the waveguide **104**.

A number of the photonic switches **100** can be assembled to form a switch fabric that can be used to transmit channels between various kinds of data processing, storing, or transmitting devices. FIG. **8** shows an exploded isometric view of a first switch fabric **800** in accordance with embodiments of the present invention. The switch fabric **800** includes a first set of three approximately parallel **801-803** waveguides intersecting a second set of three approximately parallel waveguides **805-807** all of which are disposed on a surface of a substrate **808**. The switch fabric **800** includes nine photonic switches **811-819** disposed on the surface of the substrate **808**. Each photonic switch is positioned in proximity to the intersection of two intersecting ridge waveguides, as described above with reference to FIG. **1**. As shown in FIG. **8**, the switch fabric **800** also includes a first set of three wires **821-823** and a second set of three wires **825-827** located at approximately right angles to the first set of wire **821-823**. For simplicity of illustration, the wires **821-823** and the wires **825-827** are shown detached from the wires of the photonic switches **811-819**. During operation of the switch fabric **800**, the wires in the first set of wires **821-823** are electronically coupled to the wires in the columns of photonic switches, and the wires in the second set of wires **825-827** can be photonically coupled to the wires in the rows of photonic switches. For example, the wire **821** can be electronically coupled to the wires of the photonic switches **811**, **814**, and **817**, and the wire **825** can be electronically coupled to the wires of the photonic switches **811**, **812**, and **813**. Note that the switch fabric **800** can be scaled down or up to accommodate any number of intersecting waveguides and photonic switches.

The photonic switches **811-819** can be configured and operated in accordance with the two different operational embodiments described above with reference to FIGS. **6** and **7**. For the sake of brevity, the following is a description of the operation of the switch fabric **800** in accordance with the operational embodiment described above with reference to FIG. **6**. In other words, it is assumed that the photonic switches **811-819** are configured to operate in accordance with the embodiment described above with reference to FIG. **6**. The switch fabric **800** receives three different channels λ_1, λ_2, and λ_3 on the three waveguides **801-803**, respectively. The photonic switches **811-819** can be configured so that the associated microrings are not resonant with the channels λ_1, λ_2, and λ_3 propagating along the waveguides **801-803**, respectively. For example, the photonic switches **811-813** may have associated microrings that are configured to not be in resonance with the channel λ_1, and, therefore, the channel λ_1 is not evanescently coupled via the associated microrings into the intersecting waveguides **805-807**. The photonic switches **811-819** can also be configured so that when an appropriate current is applied to the associated wires, the microrings are resonant with the channels λ_1, λ_2, and λ_3 propagating along the waveguides **801-803**. For example, when an appropriate current is applied to the wire of the photonic switch **811** via the wires **821** and **825**, the associated microring is resonant with the channel λ_1 such that the channel λ_1 evanescently couples into the waveguide **805**. When an appropriate current is applied to the wire of the photonic switch **816** via the wires **823** and **826**, the associated microring is resonant with the channel λ_2 such that the channel λ_2 evanescently couples into the waveguide **807**.

In other embodiments, rather than placing the waveguide layer and substrate **808** between the first set of wires **821-823** and the second set of wires **825-827**, the wires running through the photonic switches **811-819** can each be connected to wires as described above with reference to FIG. **5**. In other words, each of the wires running through a microring of the photonic switches **811-819** can be connected to two wires, such as wires **504** and **502**, and wires, such as wire **506**, can pass through openings in the substrate **808** to connect with wires, such as wire **508**.

In order to reduce loss of a channel due to diffraction at a waveguide intersection, such as intersection **602**, in other embodiments, the intersecting waveguides, such as waveguides **102** and **104**, can be replaced by a first waveguide that is overlain by a second waveguide. FIG. **9** shows an isometric view of a second photonic switch **900** in accordance with embodiments of the present invention. The photonic switch **900** includes a first ridge waveguide **902**, a second ridge waveguide **904** overlaying the first waveguide **902**, and a microring **906**. The first waveguide **902** and the microring **906** are disposed on a substrate **908**, and the second waveguide **904** can be in contact with the first waveguide **902** or suspended above the first waveguide **902** by a support (not shown). Although the microring **906** can be configured as described above with reference to FIGS. **2** and **3**, the height of the microring **906** is greater than the height of the microring **106** in order to evanescently couple a channel resonating in the microring **906** into the waveguide **904**. The photonic switch **900** also includes a portion of a wire **910** passing through an opening **912** in the microring **906** and an opening (not shown) in the substrate **908**. The photonic switch can be comprised of the same materials as the first photonic switch **100** and operated in the same manner as described above with reference to FIGS. **6** and **7**. In addition, configuring the photonic switch **900** with separate first and second waveguides **902** and **904** may reduce the amount of loss due to diffraction, as described above with reference to FIGS. **6** and **7**.

In other embodiments, the first waveguide **902** can be fabricated on a surface of the a substrate, as shown in FIG. **9**, and the second waveguide **904** can also be fabricated on the same substrate but with the waveguide **904** arching over the first waveguide **902** where the two waveguides cross. This configuration employs the shorter microring **106** and the same coupling as the photonic switch **900** but without the diffraction associated with the waveguides of the photonic switch **100**.

In other embodiments, the photonic switch **900** can also be employed as photonic switches in switch fabrics. FIG. **10** shows an exploded isometric view of a second switch fabric **1000** in accordance with embodiments of the present invention. The switch fabric **1000** includes a first set of three approximately parallel waveguides **1001-1003** and a second set of three approximately parallel waveguides **1005-1007** that overlay the first set of waveguides **1001-1003**. The waveguides **1001-1003** are disposed on the surface of a substrate **1008**. The switch fabric **1000** also includes nine photonic switches **1011-1019** disposed on the surface of the substrate **1008**. The photonic switches **1011-1019** are positioned in proximity to two overlaying ridge waveguides, as described above with reference to FIG. **9**. As shown in FIG. **10**, the switch fabric **1000** also includes a first set of three wires **1021-1023** and a second set of three wires **1025-1027** located at approximately right angles to the first set of wire **1021-1023**. For simplicity of illustration, the wires **1021-1023** and the wires **1025-1027** are shown detached from the wires of the photonic switches **1011-1019**. The wires in the first set of wires **1021-1023** are electronically coupled to the wires in the columns of photonic switches, and the wires in the second set of wires **1025-1027** can be photonically coupled to the wires in the rows of photonic switches. For example, the wire **1021** can be electronically coupled to the wires of the photonic switches **1011**, **1014**, and **1017**, and the wire **1025** can be electronically coupled to the wires of the photonic switches **1011**, **1012**, and **1013**. The photonic switches **1011-1019** can operated in the same manner as the photonic switches of the switch **800** described above with reference to FIG. **8**. Note that the switch fabric **1000** can be scaled down or up to accommodate any number of overlapping waveguides and photonic switches.

In order to reduce the loss associated with not fully evanescently coupling a channel into a first microring, as described above with reference to FIGS. **6** and **7**, a second microring can be employed. FIG. **11** shows an isometric view of a third photonic switch **1100** in accordance with embodiments of the present invention. The photonic switch **1100** is identical to the photonic switch **100** except the photonic switch **1100** includes an additional tunable microring resonator **1202** disposed on the surface of a substrate **1104** opposite the microring **906**. The photonic switch **1100** also includes a second wire **1106** passing through an opening **1108** in the microring **1102** and an opening (not shown) in the substrate **1104**. The elements of the photonic switch **1100** can be comprised of the same materials as the first photonic switch **100**, and the microring **1102** can have the same configuration and be comprised of the same materials as the microrings **200** and **300** described above with reference to FIGS. **2** and **3**.

The microrings **106** and **1102** are operated by applying appropriate currents to the wires **110** and **1106**, as described above with reference to FIGS. **6** and **7**. For example, the microrings **106** and **1102** can be configured in the same manner as the microrings described above with reference to FIG. **6**. Applying an appropriate current to the wire **110** causes the resonance of the microring **106** to shift into resonance with a channel propagating along the waveguide **104**. Although, a substantial portion of this channel evanescently couples from the waveguide **104** into the waveguide **102** via the microring **106**, a portion of the channel may continue to propagate beyond the intersection **602**. Applying an appropriate second current to the wire **1106** causes the resonance of the microring **1102** to shift into resonance with the channel, evanescently coupling more of the channel into the waveguide **102**. As a result, loss resulting from a portion of the channel passing the microring **106** without being coupled into the microring **106** may be reduced by including the microring **1102**.

In other embodiments, the channel loss prevention measures of the photonic switches **900** and **1100** can be combined to form a fourth photonic switch. FIG. **12** shows an isometric view of a fourth photonic switch **1200** in accordance with embodiments of the present invention. The photonic switch **1200** is identical to the photonic switch **900** except the photonic switch **1200** includes an additional tunable microring resonator **1202** disposed on the surface of a substrate **1204** and a wire **1206** passing through a hole **1208** in the microring **1202** and a hole (not shown) in the substrate **1204**. The elements of the photonic switch **1200** can be comprised of the same materials as the first photonic switch **100**, and the microring **1202** can have the same configuration and be comprised of the same materials as the microrings **200** and **300** described above with reference to FIGS. **2** and **3**.

Although the present invention has been described in terms of particular embodiments, it is not intended that the invention be limited to these embodiments. Modifications within the spirit of the invention will be apparent to those skilled in the art. For example, in other embodiments of the present invention, those skilled in the art will immediately recognize that the switch fabric **800** can be modified to include the photonic switches **1100** at intersecting waveguides, and that the switch fabric **1000** can be modified to include the photonic switches **1200** at the overlaying waveguides.

The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that the specific details are not required in order to practice the invention. The foregoing descriptions of specific embodiments of the present invention are presented for purposes of illustration and description. They are not intended to be exhaustive of or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations are possible in view of the above teachings. The embodiments are shown and described in order to best explain the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following claims and their equivalents:

The invention claimed is:

1. A photonic switch comprising:

a first waveguide disposed on a surface of a substrate in proximity to an opening in the substrate;

a second waveguide crossing the first waveguide and positioned in proximity to the opening in the substrate;

a tunable microring resonator disposed on the surface of the substrate adjacent to the first waveguide and the second waveguide and having an opening aligned with the opening in the substrate; and

a wire that passes through the opening in the microring and the opening in the substrate, wherein an appropriate current applied to the wire generates a magnetic field in the microring, the magnetic field shifts resonance of the microring in order to switch electromagnetic radiation between the first and second waveguides.

2. The photonic switch of claim **1** wherein the substrate further comprises a material selected from the group consisting of:

SiO_2;

Al_2O_3;

Si_3N_4; and

any other suitable dielectric material.

3. The photonic switch of claim **1** wherein the first ridge waveguide and the second ridge waveguide further comprise a material selected from the group consisting of:

a column IV semiconductor;

a III-V compound semiconductor; and

a II-VI compound semiconductor.

4. The photonic switch of claim **1** wherein the microring further comprises:

an inner microring; and

a magnetized outer layer.

5. The photonic switch of claim **4** wherein the inner microring further comprises a material selected from the group consisting of:

a semiconductor doped with Mn, Cr, Ni, Fe, Co, alloys thereof, and terbium;

other suitable rare earth ions;

other suitable 3d ions with unfilled d-shells;

terbium doped borosilicate glass; and

terbium gallium garnet crystal.

6. The photonic switch of claim **4** wherein the magnetized outer layer further comprises a material selected from the group consisting of:

iron;

nickel;

permalloy; and

another suitable ferromagnetic material.

7. The photonic switch of claim **1** wherein the tunable microring resonator further comprises:

an inner microring;

an outer dielectric layer covering at least a portion of the outer surface of the inner microring;

a ferromagnetic segment covering at least a portion of the outer surface of the outer dielectric layer; and

an antiferromagnetic pinning stub covering at least a portion of the outer surface of the ferromagnetic segment.

8. The photonic switch of claim **7** wherein the inner microring further comprises an intrinsic semiconductor.

9. The photonic switch of claim **1** further comprises:

a second tunable microring resonator disposed on the surface of the substrate adjacent to the first waveguide and the second waveguide and having an opening aligned with a second opening in the substrate; and

a second wire that passes through the opening in the second microring and the second opening in the substrate.

10. The photonic switch of claim **1** wherein the second waveguide crossing the first waveguide further comprise the second waveguide disposed on the surface of the substrate and intersecting the first waveguide.

11. The photonic switch of claim **1** wherein the second waveguide crossing the first waveguide further comprise the second waveguide overlaying the first waveguide.

12. The photonic switch of claim **1** further comprises:

a first wire electronically coupled to a first end of the wire; and

a second wire electronically coupled to a second end of the wire.

13. A switch fabric comprising:

a first set of approximately parallel waveguides disposed on a surface of a substrate;

a second set of approximately parallel waveguides, each waveguide in the second set crossing each waveguide in the first set; and

a set of photonic switches, wherein each photonic switch is disposed on the surface of a substrate adjacent to each crossing of a waveguide from the first set with a waveguide from the second set, and wherein each photonic switch includes a wire that passes through the photonic switch so that application of an appropriate current to the wire generates a magnetic field in the photonic switch that shifts resonance of the photonic switch to switch electromagnetic radiation between the first and second waveguides.

14. The photonic switch of claim **13** wherein each waveguide in the second set crossing each waveguide in the first set further comprise each waveguide in the second disposed on the surface of the substrate and intersecting each waveguide in the first set.

15. The photonic switch of claim **13** wherein each waveguide in the second set crossing each waveguide in the first set further comprise each waveguide in the second overlaying each waveguide in the first set.

16. The switch fabric of claim **13** wherein each photonic switch in the set of photonic switches further comprises:

a first tunable microring resonator disposed on the surface of the substrate adjacent to a waveguide from the first set and adjacent to a waveguide from the second set and includes an opening aligned with a first opening in the substrate; and

the wire passes through the opening in the first microring and the first opening in the substrate, wherein the appropriate current applied to the wire generates a magnetic field in the first microring, the magnetic field shifting resonance of the first microring to switch electromagnetic radiation between the first and second waveguides.

17. The switch fabric of claim **16** wherein the first tunable microring resonator further comprises:

an inner microring; and

a magnetized outer layer.

18. The switch fabric of claim **13** wherein the first tunable microring resonator further comprises:

an inner microring;

an outer dielectric layer covering at least of portion of the outer surface of the inner microring; and

a magnetized segment covering at least a portion of the outer surface of the outer dielectric layer.

19. The switch fabric of claim **13** further comprises:

a second tunable microring resonator disposed on the surface of the substrate adjacent to a waveguide from the first set and adjacent to a waveguide from the second set and includes an opening aligned with a second opening in the substrate; and

a second wire that passes through the opening in the second microring and the second opening, wherein the appropriate current applied to the second wire generates a magnetic field in the second microring, the magnetic field shifts resonance of the second microring to switch electromagnetic radiation between the first and second waveguides.

20. The switch fabric **13** further comprises:

a first set of wires, each wire of the first set of wires electronically coupled to at least one of the photonic switches; and

a second set of wires, each wire of the second set of wires electronically coupled to at least one of the photonic switches.

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